JUNE 2023

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The World's Most Boring Number

Treating Multiple Personality Disorder

Weather Disasters and Climate Change



Star Power

What is the future of fusion energy?

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Illustration by Mark Ross.

Photograph by Spencer Lowell

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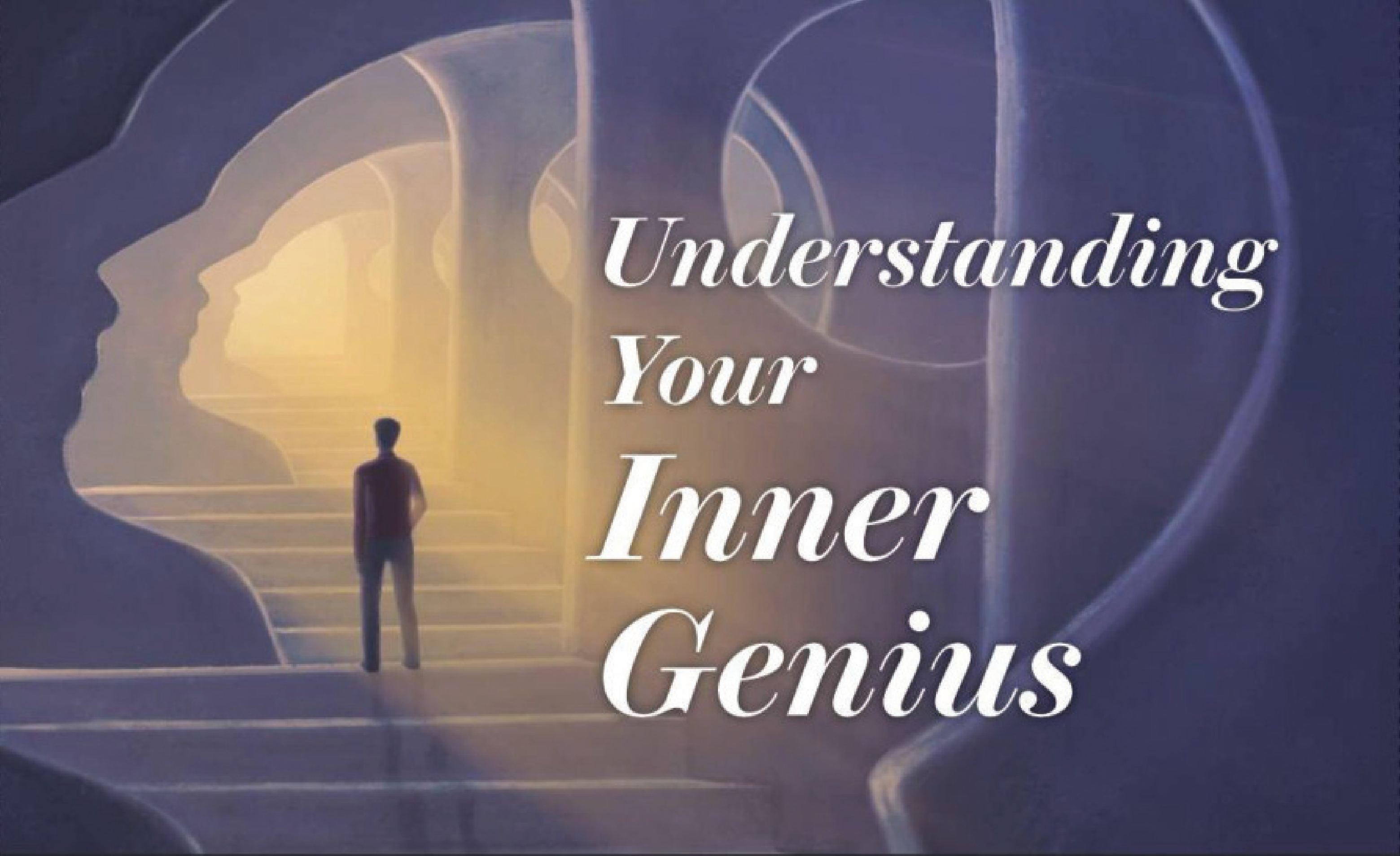
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Laura Helmuth is editor in chief of *Scientific American.* Follow her on Twitter @laurahelmuth

Big Questions

You know a story is going to be fun when it starts with a question that makes you laugh: What is the most boring number in the world? It's a legitimate mathematical question, and it turns out there are interesting numbers (prime numbers, powers of 2) and not-so-interesting numbers. You can probably anticipate the paradox: If a number is especially boring, doesn't that make it interesting? Theoretical physicist Manon Bischoff, who is an editor for our partner publication *Spektrum* in Germany, shows on page 76 how to sort numbers for boringness and why it matters.

I admit I was skeptical when we first started discussing a story proposal about treating a person with multiple personalities. Weren't some of the classic cases exaggerated or made up? But the fascinating account of "Ella" by therapist and anthropologist Rebecca J. Lester on page 36 explains how dissociative identity disorder can develop and manifest. It's a hopeful and generous story that takes us inside the therapeutic process and reveals how someone can start to heal from extreme trauma.

When a weather disaster strikes, people want to know whether climate change is to blame. And if so, to what degree? The field of "attribution science" has advanced dramatically in the past decade. As investigative journalist Lois Parshley writes on page 44, researchers are now able to say how much worse or more likely floods, hurricanes, wildfires, droughts, and other disasters were made by the human-caused climate crisis. This knowledge can help people respond to unfolding disasters and plan for future ones.

Drug-resistant hookworms are spreading among pet dogs, and researchers have traced their origins to greyhounds raised for racing. The parasites can kill puppies and occasionally cause nasty infections in people. On page 70, science journalist Bradley van Paridon describes how the superparasite evolved and traveled through greyhound racetracks, rescue dogs and dog parks.

Electrons move in mysterious ways. They're too fast to observe in detail as they jump through crystals or perform feats of quantum tunneling that let them escape energy barriers. To understand the bizarre properties of matter, physicists are creating models made of light. Physicist Charles D. Brown II on page 52 shares how his light-based version of graphene lets him study how particles behave in a crystal lattice. In the author's words, "Quantum physics is a trip!"

Some of the most distinctive languages on Earth are still spoken, but just barely, by people who live on the Andaman Islands off the coast of India. Andamanese people arrived to the archipelago about 50,000 years ago, and according to genetic and linguistic studies, they were largely isolated until recently. Linguist Anvita Abbi worked with the last speakers of several local languages to preserve and understand their heritage (*page 62*). She discovered that the grammar of Andamanese languages is fundamentally based on the parts of the body, unlike any known language family.

What's the future of fusion? Is it always going to be another 20 or 30 or 50 years away? In our cover story beginning on page 28, author Philip Ball examines recent advances in fusion energy, including the first reaction that created more energy than was used to trigger it. Fusion will not be part of our urgently needed transition from fossil fuels to renewable energy. But there's still a chance it could succeed … in another 20 or 30 or 50 years. Ball cuts through the hype and explores the physical limitations and opportunities of the energy that powers stars. SA

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February 2023

> **"It is up to the scientific community to create the political will to address the control of low-Earth orbit satellite proliferation."**
>
> DARRALL CUTTING *FORESTVILLE, AUSTRALIA*

A LONGTIME READER'S TALE

I began reading *Scientific American* at a single-digit age. My first mind-blowing article was Allan R. Sandage's "The Red-Shift" in 1956. *SciAm* has gone through ups and downs, but in my view, in the past few years it has been better than ever. Bravo to all of you!

Christopher Clark *Houston, Tex.*

SOLAR STORMS VS. SATELLITES

"The Threat of Satellite Constellations," by Rebecca Boyle, highlights the truly existential threat the growing number of orbital spacecraft poses to Earth-based astronomy, as well as the lack of political will to even address it. After all, what's a bit of twinkling in the sky compared with the profits to be made from making the Internet available everywhere and to anyone on Earth? What the article misses is the extreme danger of a coronal mass ejection (CME) of the strength of the Carrington Event of 1859, which even then caused complete disruption and fires in telegraph stations. A massive CME's effect on our modern technological civilization would be catastrophic.

What would happen to the thousands of new satellites in low-Earth orbit (LEO)? The CME would destroy their electronics, the satellite constellations would disintegrate, and collisions would inevitably begin to occur, each generating high-velocity fragments. A chain reaction would result, and LEO would become a barrier that would effectively prevent humankind's access to space! It is up to the scientific community to create the political will to address the control of LEO satellite proliferation because it is in the interest of everybody, not just astronomers.

Darrall Cutting *Forestville, Australia*

BOYLE REPLIES: A geomagnetic storm akin to the record-holding Carrington Event, named for the British astronomer who saw the solar flare that preceded the storm, would be catastrophic for objects in orbit, in cislunar space and on Earth. But solar activity needn't be that extreme to have an impact. As my story reports, geomagnetic activity in February 2022 caused 40 newly launched Starlink satellites to lose altitude and burn up in Earth's atmosphere. A more powerful storm could indeed start a chain reaction of failed satellites crashing into one another.

A solar storm is not the only thing that could cause this disastrous phenomenon, which is known as the Kessler syndrome. Short of reducing the number of objects in LEO, the best safeguard against CMEs may be to predict solar activity and ensuing geomagnetic storms with greater accuracy. Better forecasts could provide enough warning for astronauts to seek shelter and for satellite operators to take protective measures. Sun-observing spacecraft launched in the past five years could improve those storm predictions.

SINGULAR LIFE

"Life as We Don't Know It," by Sarah Scoles, mentions the seemingly unavoidable criterion that all life involves reproduction. But I fail to see why reproduction is a necessity. Surely it is possible for a living entity to be immortal, sentient, distinct from its environment, metabolizing and even moving around without necessarily having to reproduce. There are at least two well-known science-fiction novels about such possible entities: *Solaris,* by Stanisław Lem (1961), and *The Black Cloud,* by Fred Hoyle (1957).

Robert Cailliau
Prévessin-Moëns, France

SCOLES REPLIES: It's true that the inclusion of reproduction, or at least the ability to reproduce, is standard for most definitions of life. But that does ignore pesky complications, a classic one being the mule: an animal that everyone can agree is alive but that typically cannot make more of itself, with or without genetic variations. And flame, which can make more of itself, is not alive. On the topic of aging, Earth does actually have organisms that are functionally immortal, such as hydras. All of this is to say that the reproduction criterion isn't black-and-white, and neither is the definition of life. Humans will probably keep searching for versions of both the definition and life beyond Earth for a long time.

ANTARCTIC HIGH RISE

"The Coming Collapse," by Douglas Fox [November 2022], describes the impending disintegration of the Thwaites Glacier, which will contribute to sea-level rise. I have questions about what happens after the glacier's demise.

As I remember, ice's displacement of water remains the same when that ice melts. Thus, there will be no further increase in sea-level rise if ice that is already floating detaches from the main glacier. Is that correct? Additionally, the more apocalyptic stories about Thwaites seem to suggest it will fall into the ocean with a big splash. Does it work that way, or does the glacier slide in over the course of days, weeks, months or years?

Fred Brunyate *via e-mail*

FOX REPLIES: Because an ice shelf is already floating, its melting does not di-

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rectly *contribute to sea-level rise. Once the ice shelf is gone, however, the glaciers behind it accelerate their flow into the ocean—and this does increase sea level. After the collapse of the Larsen A and B and Prince Gustav ice shelves on the Antarctic Peninsula, the flow of the glaciers they had buttressed accelerated by twofold to ninefold. Much of this speedup happened within months. Thwaites's slide into the ocean won't necessarily accelerate that much when its ice shelf finally dies. But even the mere thinning and shrinking of the ice shelf to date have allowed the glacier's flow to accelerate. The nearby Pine Island Glacier has similarly seen a flow speedup of about 70 percent. The Thwaites and Pine Island Glaciers are so huge, compared with the little glaciers on the Antarctic Peninsula, that even their more moderate acceleration will contribute far more to sea-level rise.*

The Thwaites Glacier covers an area approximately the size of Florida, and it's not all going to slide into the ocean immediately. So its "full" collapse will take centuries. But the big concern is that once Thwaites loses its ice shelf and its grounding line retreats past a certain point, the glacier will be inherently unstable. We'll have committed future humanity to the full amount of sea-level rise—even if it takes centuries to unfold.

ERRATA

"Concrete Cure," by Mark Fischetti, Nick Bockelman and Wil V. Srubar, should have said that the process of converting lime into clinker involves the lime sintering (fusing), not both sintering and melting. It also should have said that adding mineralizer to the lime would lower its sintering temperature, not its melting temperature.

"Striking Back," by Allison Parshall [Advances, April 2023], should have said the laser consumes about 10 kilowatts, not 10 kilowatts per hour.

In "Imaginary Universe," by Marc-Olivier Renou, Antonio Acín and Miguel Navascués [April 2023], two of the equations in the opening illustration should have been given as $i^5 = i$ and $i^8 = 1$, not $i^5 = 1$ and $i^8 = \sqrt{-1}$. And the box "What Are Imaginary Numbers?" should have said that rational numbers include the integers, not that "rational numbers are the integers."

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Regulate Nutraceuticals

These products' claims are often not verified, posing efficacy and safety issues

By the Editors

Nutraceuticals are a class of products such as pills, powders, bars and tinctures with ingredients derived from plant and animal food products. Their manufacturers claim that, among other things, these supplements can fight cancers or heart disease, boost gut health or improve general wellness. Pharmacy aisles and Internet ads are chockablock with these products, which are something between vitamins and processed foods (many, but not all, nutraceuticals contain vitamins). Market research estimates they were worth around $400 billion globally in 2021.

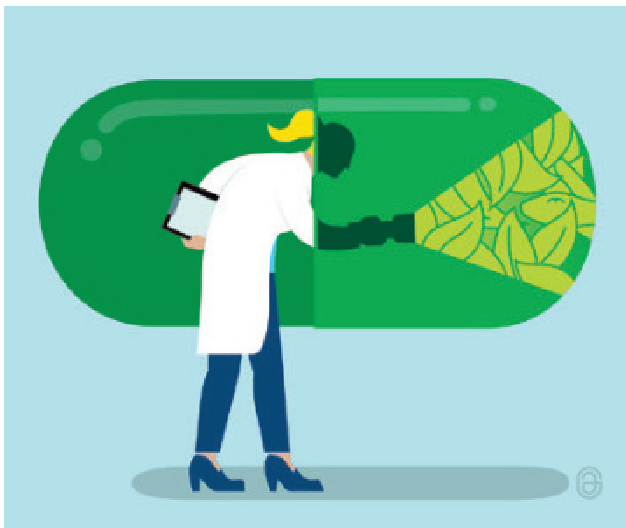
But some items in this market could pose a threat to human health and safety, and Congress should empower the Food and Drug Administration to start treating these products (as well as vitamins and mineral supplements) more like drugs. Right now no federal agency fully oversees the clinical testing and chemical verification of nutraceuticals in the U.S., and these products are often plagued by quality and safety problems. Nutraceutical makers can perform their own testing for safety and purity, but those tests, as well as any purported health benefits, are not required to be independently verified or submitted to the FDA. Studies have found that active compounds in these products can be in different chemical forms or different quantities than what is stated on the label, so dosing can be inconsistent. Some products contain pharmaceutical compounds not allowed in dietary supplements or other ingredients not listed on the packaging. Both the Federal Trade Commission and the FDA can intervene in the event of false claims but only after the product has hit the shelves and people have spent money on it.

In contrast, the FDA regulates all prescription and over-the-counter drugs on the U.S. market. FDA approval is typically a years-long process and involves many phases of research and testing from basic efficacy (the drug does what its developers say it does) to human safety (trials involving thousands of people to measure side effects and adverse reactions). The agency also inspects plants where prescription drugs are manufactured, and it can issue drug recalls if there are problems. Beyond postmarket regulation, nutraceuticals do not have these guardrails.

It is understandable people would think these products are safe and effective. After all, many sit in pharmacies next to over-the-counter drugs. Nutraceutical companies certainly benefit from this confusion. And consumers might not closely read nutraceuticals' labels, which are required to declare that claims about the items have not been evaluated by the FDA and that they should not take the place of approved medical treatments. People might choose these products over medical interventions for serious illnesses or take one that interacts with their current medications.

A study by the Centers for Disease Control and Prevention estimated that about 23,000 emergency department visits and more than 2,000 hospitalizations every year are attributed to adverse effects of dietary supplements. Several past studies of prenatal vitamins have found them contaminated with heavy metals such as lead. In 2019 prenatal vitamin manufacturer Rainbow Light paid $1.75 million to settle a California case for falsely advertising its supplement as free of metals when an independent laboratory investigation found the pills contained lead, arsenic and cadmium. Regulators often have no way of identifying the harmful compounds in these products because many do not contain what the ingredient list says or even declare all their ingredients.

What can be done? A 2022 bill called the Dietary Supplement Listing Act would require supplement makers to register their product with the FDA and list all its ingredients, along with an explanation of how the nutrients in the supplement relate to its



health claims. But the bill doesn't give the FDA a mechanism to confirm such products' ingredients, nor can it stop companies from exaggerating claims about their effects. The agency wouldn't be able to prevent the sale of questionable supplements or inspect manufacturing facilities. Rather than protecting the consumer, some experts say, the bill could falsely bolster the credibility of supplements under the seal of new FDA oversight.

Ideally, Congress could strengthen the bill, explicitly including nutraceuticals and requiring manufacturers to conduct third-party testing for safety and efficacy and report their findings to the FDA. The FDA should be empowered to verify nutraceutical products by chemically confirming their ingredients, enforcing recalls and product bans, and maintaining a publicly searchable database of all supplement and nutraceutical health products with their associated ingredients and efficacy studies. Without drastic legislation, the consumer must evaluate potentially hyped claims alone. SA

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Illustration by Aad Goudappel

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Haider Warraich, a physician at Brigham and Women's Hospital, Harvard Medical School and the VA Boston Healthcare System, is author of *The Song of Our Scars: The Untold Story of Pain* (Basic Books, 2022).

Origins of Pain

Chronic pain is biochemical, but it's also psychological. Treatment needs to address how we think and feel about it

By Haider Warraich



Every person who has ever hurt has their pain origin story; I certainly have mine. While lifting weights one day when I was a medical student, I heard a loud click and felt my whole body go limp. As pain gripped me, I was rushed to the emergency room, where I was assured the agony would eventually disappear. It didn't. What I've learned about pain since then—both as a patient and as a physician—has me questioning how we diagnose and treat it.

In researching a book on pain, I learned about studies showing that our perception of this response to injury—and our fear of it—can play a huge role in our clinical outcomes. Such findings are opening the door to treatments that might finally help the millions of people living with chronic pain.

The traditional approach has been to find mechanical and anatomical explanations for chronic pain. Magnetic resonance imaging showed multiple damaged discs in my spine. It was the only evidence for what turned my acute injury into never-ending torment. Chronic pain is usually defined as pain that affects someone frequently for three months or more, and mine exceeded that by many years. My pain has improved, mostly because of physical therapy, but my origin story—the injury and the resulting MRI abnormalities—had little to do with the pain I felt years afterward. A. Vania Apkarian of Northwestern University, one of the world's leading pain researchers, told me the classic idea is that pain continues as long as the injury does, but the injury and pain it produces end up being separate. "The injury itself has no value," he says.

Although MRIs are reliable indicators of injury, they are not reliable indicators of pain. A review of 33 studies found that among a group of 20-year-olds without any back pain, 37 percent had disc degeneration and 30 percent had disc bulges on MRI. And in people whose backs hurt, MRI results have absolutely no correlation with their pain. In other words, an MRI doesn't help us figure out what hurts and what doesn't. These data upended my understanding of the link between pain and injury.

This is a really big deal: millions of people in the U.S. alone get MRIs and computed tomography scans for back pain, which is the most common cause of disability worldwide. Yet a recent study showed that only 5 percent of MRIs for back pain were medically justified, and of those who received MRIs, 65 percent received potentially harmful advice—including calls for generally risky back surgery that probably would not have resolved their pain.

Spinal surgeries are some of the most commonly performed procedures around the world, and in a study of people who had lumbar fusion, only 26 percent returned to work after two years, compared with 67 percent with chronic pain who didn't have surgery. I could have been one of those people who had unnecessary surgery, but when I took my MRI films to a renowned surgeon, he told me an operation might leave my back worse off. Instead I committed myself to physical therapy to lessen the pain.

If anatomy doesn't explain why pain turns chronic, what does? One major factor in whether pain becomes immortal in our bodies is our mindset. People who fear being in pain or are anxious about it are up to twice as likely to develop chronic pain after an operation. Traumatic events such as being robbed or sexually assaulted are some of the strongest predictors of chronic back pain.

A recent clinical trial revealed the power of therapies that target how we think about discomfort. Patients with chronic low back pain were split into three groups: one received usual care (painkillers and exercise); another was told it was getting a placebo (which can be quite effective for back pain). The last group received usual care plus pain-reprocessing therapy, which teaches people that the brain can construct chronic pain in the absence of an active injury and that simply reframing the threat pain represents might reduce or eliminate it. Such therapy strips chronic pain of its sharpest weapon—fear. The results were remarkable: of those who received pain-reprocessing therapy for a month, 52 percent were pain-free at one year, compared with 27 percent of those receiving placebo and 16 percent of those receiving just usual care.

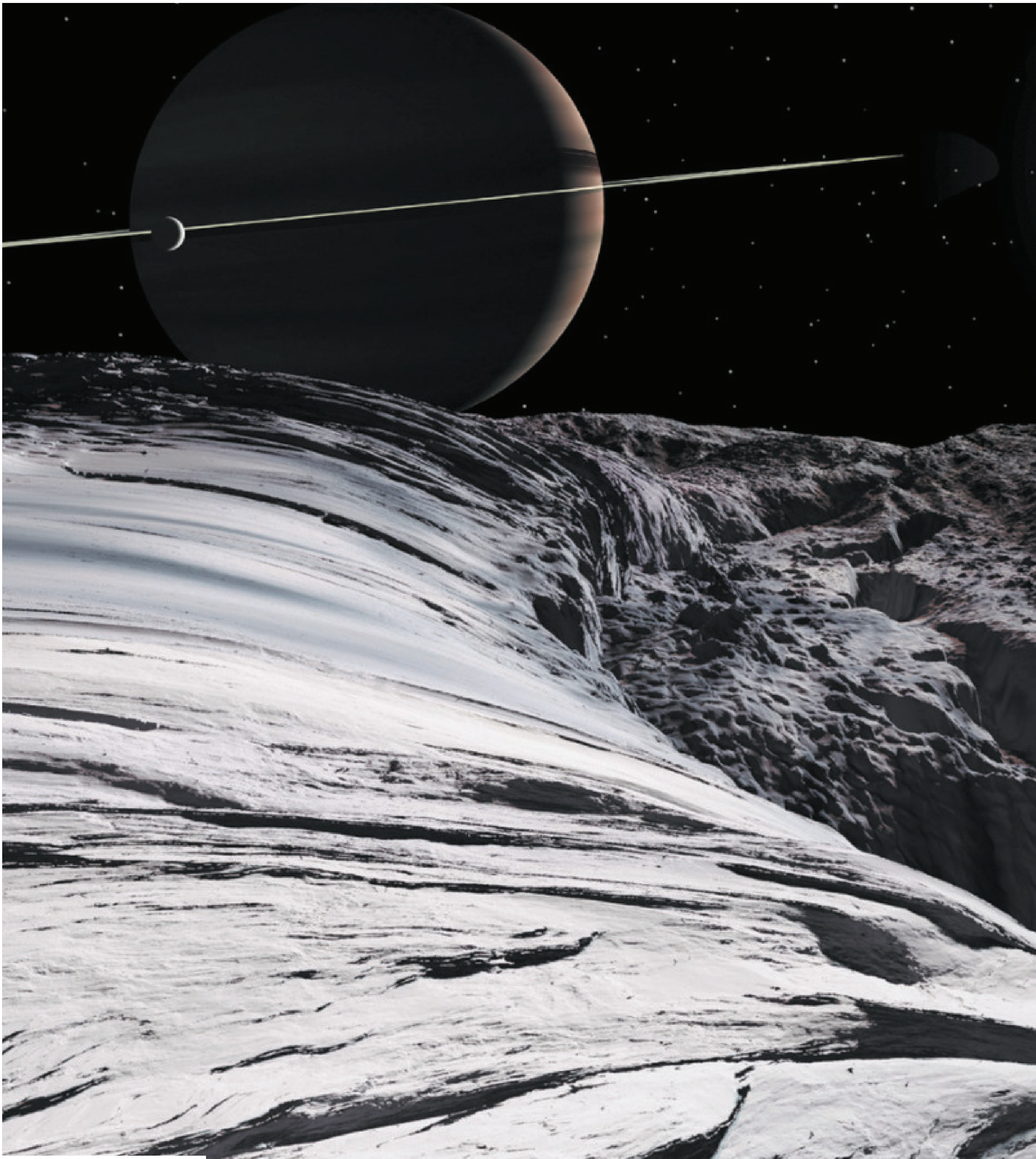
A holistic examination of pain and its origins should spur efforts to make sure everyone in agony receives kindness and respect, as well as access to more than pills and surgical procedures. Embracing the complexity of pain can open the door to new and innovative ways to ensure that even if we hurt, we don't have to suffer. SA

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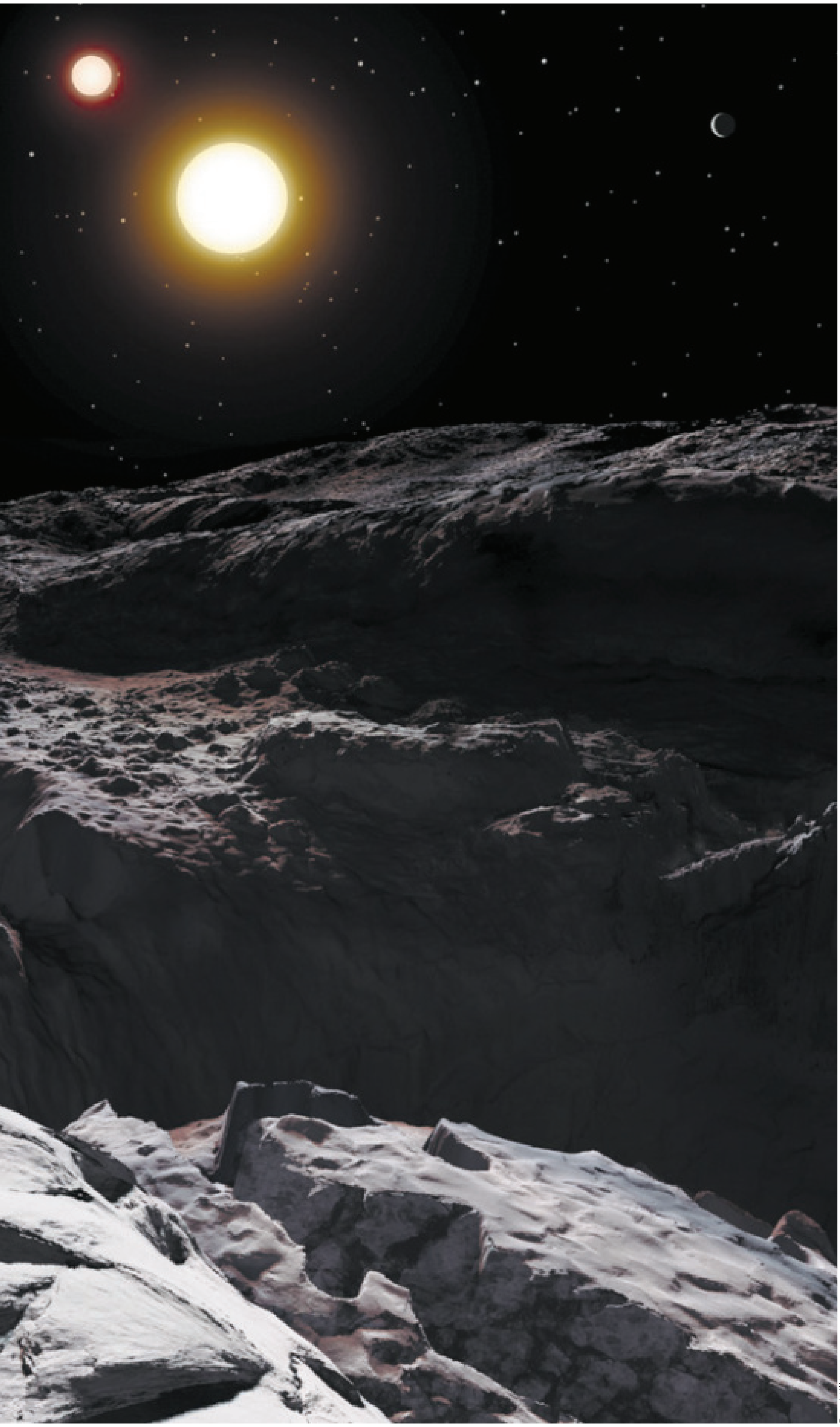
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ADVANCES



An imagined view from the Kepler-16 planetary system

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Ron Miller

INSIDE

- Squishy new material acts as an electrical conductor
- Lizards smell the size of their foes
- "Cute" and "ugly" lorises are actually two different species
- What does a tip-of-the-tongue feeling really mean?

PLANETARY SCIENCE

Order from Chaos

We live in the rarest type of star system

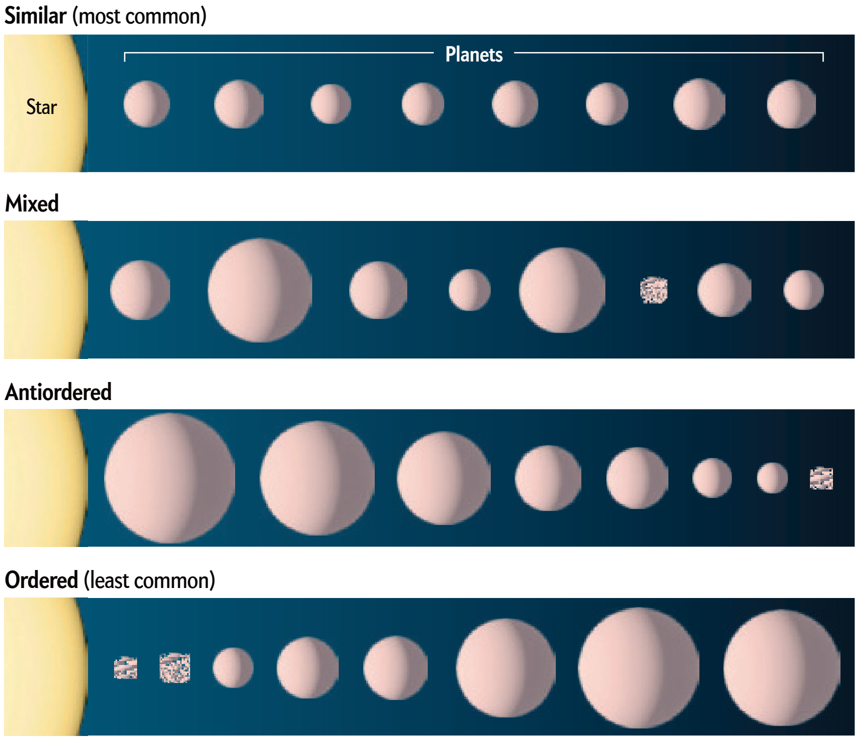
A planetary system is shaped at the boundary of order and chaos. It starts out as a molecular cloud—a big, cold clump of mostly hydrogen gas that can collapse to make stars. As central stars form, the remainder of the cloud flattens into a whirling protoplanetary disk that weaves together worlds from turbulent swirls of gas, ice and dust. From there larger-scale chaos can ensue as bigger planets push smaller ones around. The giant planets brawl among themselves, too, competing to rake up excess material and grow more giant still, sometimes ejecting the unlucky losers from the system in a "last planets standing" melee.

Scientists had long thought our own solar system—an "ordered" arrangement of tiny orbs closer to the sun and big ones farther out—was a typical outcome of this complex process. But NASA's planet-hunting Kepler mission revealed that most systems don't resemble our own at all, instead having "similar" configurations of closely packed worlds all nearly the same size and mass, like peas in a pod.

This disparity inspired astrophysicists

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The Four Classes of Planetary Systems



Source: "Framework for the Architecture of Exoplanetary Systems," by Lokesh Mishra et al., in *Astronomy & Astrophysics,* Vol. 670; February 2023

Lokesh Mishra, now at IBM, Yann Alibert of the University of Bern and their colleagues to investigate what other architectures might exist. This is a formidable task for modern telescopes but a question that computer models can easily explore. Through their research they noted a third system type in the observational data—a "mixed" distribution of shuffled small and large planets—and their simulations predicted one more: an "antiordered" architecture of worlds that get smaller and less massive the farther they are from their star. These findings, which appear in two studies in *Astronomy & Astrophysics,* reinforce the conclusion that similar architectures are most common and suggest that ordered systems like our own are the rarest. "In a few years, I believe, we'll have something like a 'standard model' of planetary formation," Mishra says. "And how different architectures of planetary systems emerge is a question that any standard model will have to answer."

Crucially, this research introduces a new mathematical framework for quantifying similarities among a system's planets according to any observable characteristic, such as mass or size; one number reveals the total range of values for that characteristic among the planets, and the other reflects how widely those values typically vary from planet to planet. This can help uncover patterns that reveal broad rules governing the birth and growth of planetary systems—as well as where those orderly rules break down. Matching their model's predictions to observations suggests, for instance, that similar systems' pea-pod planets emerge from sedate, low-mass protoplanetary disks, with higher-mass disks more easily making big planets—like our own system's Jupiter—that can chaotically interact to yield the three other architectures. The powerful James Webb Space Telescope and other facilities may soon be able to test some of these ideas.

University of Chicago astrophysicist Daniel Fabrycky, who was not involved with the new research, says such upcoming observations make these kinds of studies especially valuable. "This is about building some set of concepts, around which we expect to be able to make interesting conclusions in the future," he says. "And that's always a good idea because it's more scientifically robust to make predictions and then check them, rather than observing surprising things and painting on a theoretical gloss afterward." —*Lee Billings*

MATERIALS SCIENCE

Soft Conductor

Squishy snail robot shows off a new kind of electronics

Sometimes science advances at a snail's pace, but in this case that's a good thing: researchers have created a squishy material that combines polymers with liquid metal, demonstrated in a snail-like robot. Developers say this electrically conductive gel could be used to make self-healing electronic circuits and biological monitors for measuring heart and muscle activity—and maybe even lead to robot nervous systems.

The composite substance is stretchy and soft like living tissue. If it breaks or tears, the edges can be touched together to quickly re-form the material's molecular bonds without any additional heat or chemical treatment. And crucially, its developers say, it is the first such material that also conducts electricity well.

These abilities could lead to wire-free medical monitors as well as fully soft robots. "For my research, one thing that's really big is, 'How do you put mul-

ANIMAL BEHAVIOR

Smells Like Victory

Wall lizards size up their opponents using odor alone

In a world full of fierce competition, gathering intel on opponents is a matter of life or death. One common reptile called the wall lizard uses a particularly clever tactic to sniff out fights it can win—literally. A new study shows that these lizards, which can reach eight inches long and live in Europe and North America, manage to estimate a competitor's size based on chemical scent cues alone.

Male wall lizards, like many geckos and iguanas, secrete a waxy fluid from pores in their inner thighs to mark their territory. Rival lizards can smell these chemicals, called femoral secretions,

Graphic by Amanda Montañez

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College of Engineering, Carnegie Mellon University

tiple functions into a single material?'" says Lillian Chin, who develops soft robotic components as part of her own research at the Massachusetts Institute of Technology. Existing soft-bodied robots, she says, often require at least some rigid metals and silicon components. But soft, flexible living tissues can perform multiple tasks; muscles, Chin notes, both move the body and provide electrical feedback about that movement to the brain.

To build a multitasking artificial substance, researchers began with a tangle of long polymer chains soaked in a solvent to keep them supple, then carefully mixed in microscopic drops of gallium-indium liquid metal as well as tiny silver flakes. This produced a low-density gel dotted with conductive metals, through which enough electricity can flow to, for instance, power a motor.

For a recent study in *Nature Electronics*, the team used this new material in a monitor for measuring muscles' electrical activity as well as to connect power sources to motors in two basic machines: a snail-like soft robot and a toy car. The material's self-healing ability helped these simple circuits to stand up to wear and tear—and to be easily reconfigured. For example, the team cut the car's power-carrying gel "wires" and shifted their connections to power both movement and a small built-in light.

The snail example shows how one could use such material as a kind of artificial nervous tissue for soft robots, says Carnegie Mellon University mechanical engineer Carmel Majidi, the study's senior author. But truly multifunctional bots will require more intricate uses of the new material.

"In practice, we would want to have digital printing capabilities so we can make much more complex circuits that could interface with microelectronic chips, as well as other types of components that we could actually use in more sophisticated robotics and electronics applications," Majidi says. "There are so many possibilities that arise when you take machines and robots out of the hard case and engineer them out of materials that are soft and squishy." —*Sophie Bushwick*

with a simple flick of their tongues. Scientists have long thought such secretions hold clues that let the lizards evaluate one another's sizes from afar—but "this is the first experimental demonstration confirming it," says study co-author Stefano Scali, herpetology curator at the Natural History Museum of Milan in Italy. The results were published in *Behavioral Ecology*.

Scali and his team captured 60 male wall lizards from gardens across Milan. They kept each lizard in a transparent box for three days—long enough for the lizards to claim the boxes as their territory. The researchers then placed mirrors in front of each lizard, along with plastic strips coated with secretions from other lizards of varying sizes.

The lizards only ever saw their own reflections, which they consistently mistook for enemies and became hostile toward. But they were most aggressive when exposed to secretions from similar-size or smaller individuals. They would even try to bite the mirror when presented with secretions from significantly smaller donors that they could probably take in a fight. "It seemed as if the lizard somehow learned that it is bigger and stronger, so it attacked," Scali says. Researchers still don't know how the involved chemicals reveal a lizard's size, but Scali and his colleagues have identified a handful of proteins that may play a role. Next, they plan to use genetic tools to identify the rest of the proteins in these telltale smelly fluids.

Ashwini Mohan, a herpetologist at the Natural History Museum in London, who was not involved in the study, wonders how the lizards' confrontations might change as territories shift and temperatures rise—a process that could even chemically affect the protein secretions. "It would be fascinating to see how such behavior influences their continued survival in light of climate change and changes that humans are bringing by the destruction of habitats," she says. —*Saugat Bolakhe*



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MATHEMATICS

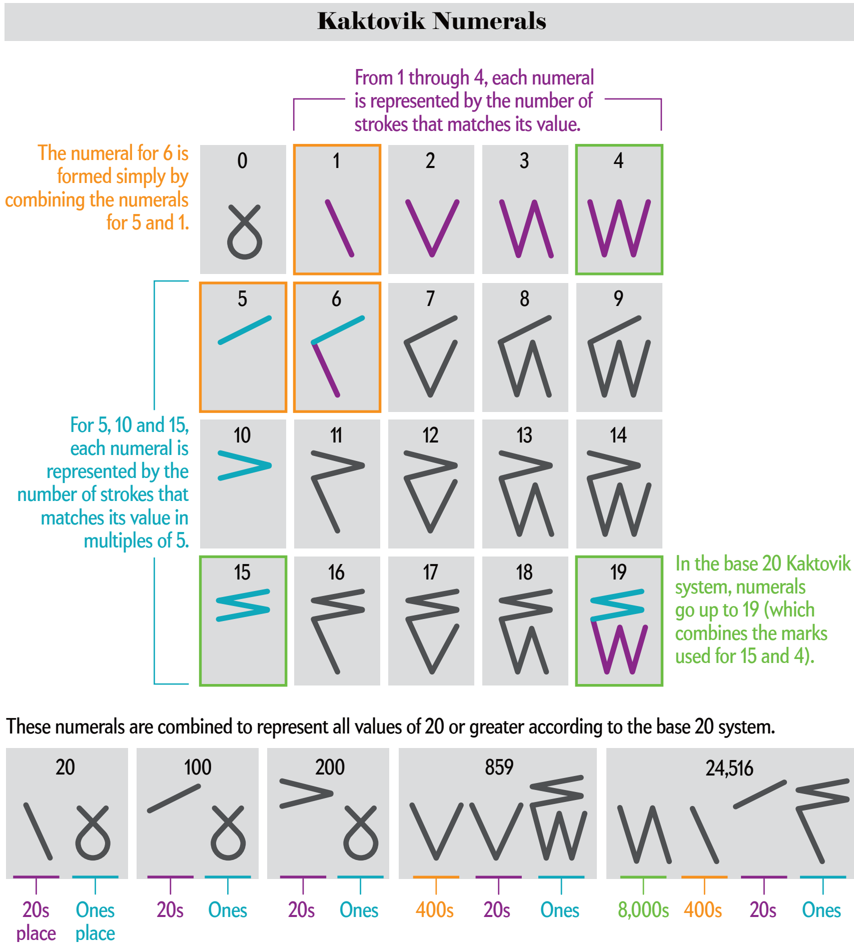
Arctic Arithmetic

Inuit schoolchildren's unique numeral system is going digital

In the remote Arctic almost 30 years ago, a group of Inuit middle school students and their teacher invented the Western Hemisphere's first new numeral system in more than a century. The "Kaktovik numerals," named after the Alaskan village where they were created, looked utterly different from decimal system numerals and functioned differently, too. But they were uniquely suited for quick, visual arithmetic using the traditional Inuit oral counting system, and they swiftly spread throughout the region. Now, with support from Silicon Valley, they will soon be available on smartphones and computers—creating a bridge for the Kaktovik numerals to cross into the digital realm.

Today's numerical world is dominated by the Hindu-Arabic decimal system. This system, adopted by almost every society, is what many people think of as "numbers"—values expressed in a written form using the digits 0 through 9. But other number systems exist, and they are as varied as the cultures they belong to.

The Alaskan Inuit language, known as Iñupiaq, uses an oral counting system built around the human body. [For another example, see "Whispers from Deep Time," by Anvita Abbi, on page 62.] Quantities are first described in groups of five, 10 and 15, and then in sets of 20. The system "is really the count of your hands and the count of your toes," says Nuluqutaaq Maggie Pollock, who taught with the Kaktovik numerals in Utqiagvik, a city 300 miles northwest of where they were invented. For example, she says, *tallimat*—the Iñupiaq word for 5—comes from the word for arm: *taliq*. "In your one arm, you have *tallimat* fingers," Pollock explains. *Iñuiññaq,* the word for 20, represents a whole person. In traditional practices, the body also serves as a mathematical multitool. "When my mother made me a parka, she used her thumb and her middle finger to measure how many times she would be able to cut the material," Pollock says. "Before yardsticks or rulers, [Iñupiat people] used their hands and fingers to calculate or measure."



During the 19th and 20th centuries American schools suppressed the Iñupiaq language—first violently and then quietly. "We had a tutor from the village who would help us blend into the white man's world," Pollock says of her own education. "But when my father went to school, if he spoke the language, they would slap his hands. It was torture for them." By the 1990s the Iñupiaq oral counting system was dangerously close to being forgotten.

The Kaktovik numerals started as a class project to adapt the counting system to a written form. The numerals, based on tally marks, "look like" the Iñupiaq words they represent. For example, the Iñupiaq word for 18, *"akimiaq pinasut,"* meaning "15-3," is depicted with three horizontal strokes, representing three groups of 5 (15), above three vertical strokes representing 3.

"In the Iñupiaq language, there wasn't a word for 0," says William Clark Bartley, the teacher who helped develop the numerals. "The girl who gave us the symbol for 0, she just crossed her arms above her head like there was nothing." The class added her suggestion—an X-like mark—to their set of unique numerals for 1 through 19 and invented what mathematicians would call a base 20 positional value system. (More technically, it is a two-dimensional positional value system with a primary base of 20 and a subbase of 5.)

Because of the tally-inspired design, arithmetic using the Kaktovik numerals is strikingly visual. Addition, subtraction and even long division become almost geometric. The Hindu-Arabic digits are an awkward system, Bartley says, but "the students found, with their numerals, they could solve problems a better way, a faster way."

"The Iñupiaq way of knowing is often done by showing," adds Qaġġuna Tenna Judkins, director of Iñupiaq education in northern Alaska's North Slope Borough. Visualizing arithmetic makes the concepts

Source: "Unicode Request for Kaktovik Numerals," by Eduardo Marín Silva and Catherine Strand. Submitted to Unicode Technical Committee Document Registry, March 16, 2021 (*reference*)

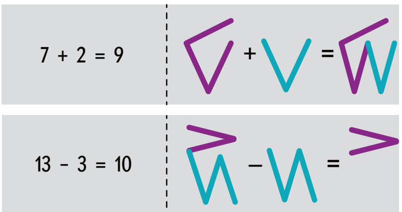
Graphics by Amanda Montañez

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Solving Equations

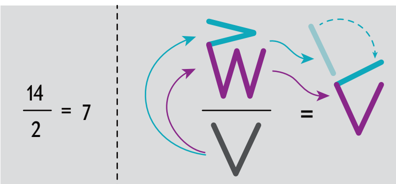
Addition and Subtraction

Kaktovik numerals can make math visually intuitive, as these simple equations demonstrate.



Simple Division

This visual intuitiveness can help simplify division in particular.

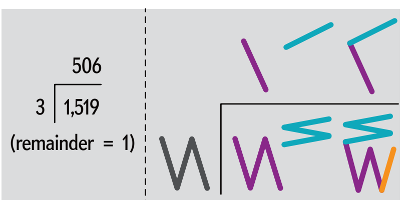


Here the symbol for 2 appears twice in the bottom part of the numerator, so the bottom part of the solution is 2.

The symbol for 2 appears once in the top part of the numerator, but rotated, so the top part of the solution is 1, rotated.

Long Division

Similar visual logic can work with long division. Leftover marks reveal the remainder.



a lot easier to understand, she says.

At first, students would convert their assigned math problems into Kaktovik numerals to do calculations, but middle school math classes in Kaktovik began teaching the numerals in equal measure with their Hindu-Arabic counterparts in 1997. Bartley reports that after a year of the students working fluently in both systems, scores on standardized math exams jumped from below the 20th percentile to "significantly above" the national average. And in the meantime, the board of education in the North Slope Borough's district seat, Utqiagvik, passed a resolution that spread the numerals almost 500 miles along the Arctic coast. The system was even endorsed by the Inuit Circumpolar Council, which represents 180,000 Inuit across Alaska, Canada, Greenland and Russia.

But under the federal No Child Left Behind Act, from 2002 to 2015, schools faced severe sanctions—or even closure—for not meeting state standards, provoking a "scare" that some local educators say squeezed the Kaktovik numerals into a marginal role despite the system's demonstrated educational impact. "Today the only place [they're] really being used is in the Iñupiaq language classrooms," says Chrisann Justice, the North Slope Borough's Iñupiaq education department specialist. "We're just blowing on the coal."

But support from Silicon Valley is helping to reignite the Kaktovik numerals. Thanks to efforts by linguists working with the Script Encoding Initiative at the University of California, Berkeley, the numerals were included in the September 2022 update of Unicode, an international information technology standard that lets the world's written languages be digitized. The new release, Unicode 15.0, provides a virtual identifier for each Kaktovik numeral so developers can incorporate them into digital displays. "It really is revolutionary for us," Judkins says. "Right now we have to either use photos of the numerals or write them by hand."

There is still work to be done. Google is building a font for the numerals based on the Unicode update, says Craig Cornelius, a Google software engineer who works to digitally preserve endangered languages. The company made a "prelease" of its font available for computer download in March, although it won't appear on the Android operating system until at least late summer. Desktop and mobile keyboards with the numerals need to be produced as well.

But excitement over the traditional system's cyber debut is growing. "If we went to a math textbook creator and said, 'Hey, can you build us a textbook but convert the Arabic numerals into Kaktovik numerals?' it would be that much easier," Judkins says.

Unicode inclusion also pushes the boundary of what is mathematically feasible with the Kaktovik numerals. At higher levels, mathematics becomes an increasingly digital discipline. The basic theory can be illustrated on a blackboard, but complex problems often need to be solved with a computer. Without digital availabil-

Continued on page 16

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Continued from page 15

ity, the Kaktovik numerals would be confined to their arithmetic wheelhouse at a time when the Iñupiaq language is being revitalized for broad modern use. Being able to input the Kaktovik numerals into computation engines such as WolframAlpha, Judkins says, is "going to be a game changer. You are almost going to be able to choose: Am I going to be in English, or am I going to be in Iñupiaq? And if I am in Iñupiaq, I'm using all Kaktovik numerals."

Nearly 3,000 miles away, in Oklahoma, Unicode holds similar promise for Cherokee communities. In the early 1800s Cherokee polymath Sequoyah invented the Cherokee syllabary of written characters. "Around the same time, he also developed a number system," says Roy Boney, language program manager for the Cherokee Nation. But Cherokee numerals weren't endorsed by the tribal government until 2012. A long history of trade with French and British settlers meant the Hindu-Arabic numerals were already in use when Cherokee numerals were invented.

It is unclear if Cherokee numerals have since gained traction, but Boney reports that interest in the system is growing. "We have the numbers and need to use them," he says. "It's been a slow roll, but we have been introducing the numbers into our education settings"—beginning to demonstrate the community use needed for inclusion in Unicode. Once the numerals are included, Boney and his colleagues hope to create a programming language using Cherokee script and numbers.

Hindu-Arabic numerals' ubiquity is powerful and has often come at the expense of culturally meaningful systems. But now those systems are slowly going digital, which is creating opportunities for their use that would have been unthinkable even two years ago. As Pollock puts it: "This is just the beginning."

—Amory Tillinghast-Raby



Cleaner wrasse approaches a parrotfish.

ANIMAL COGNITION

Fishy Photoshop

An inches-long fish can recognize its face in photos

Bluestreak cleaner wrasses are entrepreneurial fish. This tiny, shiny species sets up shop in coral reefs, where it eats parasites off of client fish, some of them big and hungry. It's a dangerous business that requires impeccable social skills. No wonder, then, that these fish can identify other individuals by their faces—and even recognize their own, according to a recent study in the *Proceedings of the National Academy of Sciences USA*. After a week with a mirror in their tank, cleaner wrasses seem able to spot themselves in photos. The researchers say this recognition suggests the fish are self-aware, a controversial interpretation.

"Fish are much more clever than previously believed," says the study's senior author Masanori Kohda, a comparative cognitive scientist at Osaka Metropolitan University in Japan. In 2019 his team published the first evidence that fish can recognize themselves in mirrors. For that study, the researchers put a parasitelike mark on cleaner wrasses' throats; when the fish saw their reflection, they rubbed themselves on rocks to remove the dot.

"Every possible imaginable creature" has been given similar tests, says Alain Morin, a cognitive psychologist at Mount Royal University in Canada, who was not involved in the study. Chimps and orangutans pass, although most other animals fail—possibly because the task doesn't mesh with many species' natural behaviors.

So what mental skills let cleaner fish succeed? Kohda's team tested whether mirror-acquainted fish could recognize their own faces in a still image. Each fish examined four photos: one of itself, one of an unfamiliar cleaner wrasse, one of its own face on the stranger's body, and one of its own body with the stranger's face. Cleaner wrasses behaved aggressively toward the ones with the stranger's face but not with their own. If the photos with their face had a parasitelike mark, they tried to scrape it off their real bodies.

To Kohda, this reaction suggests these fish have "private self-awareness," or a mental-image understanding of themselves. Morin, however, disagrees that mark tests can reveal such cognitive capability. In a photo, "you don't see your thoughts. You don't see your emotions. You see your body," he says, adding that connecting this behavior to the fish's internal world rests on many unproven assumptions.

Still, the results do show these fish possess an "ability to flexibly adjust their behavior," says University of Cambridge marine behavioral ecologist Katie Dunkley, who was not involved in the study. Given that their lives depend on customer service, she says, facial-recognition skills make sense.

Such experiments can reveal insight into another being's perspective on the world. The authors plan to test other sea creatures and probe what self-awareness might mean in organisms without language. But for now the minds of fish are still unknowable.

—Allison Parshall

atese/Getty Images

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ECOLOGY

Loris Division

"Cute" and "ugly" lorises are actually two species

Wide-eyed, arboreal lorises—small mammals that secrete flesh-rotting venom to use in vicious territorial fights—are among the planet's strangest primates. And because they live in trees and are nocturnal, they are exceptionally difficult to study. "I've gone out for 10 nights in a row and not seen any," says American Museum of Natural History conservation biologist Mary Blair.

In fact, there's so little information available, Blair says, that "every time somebody looks at lorises, they find something new"—even a new species. Discovery of primate species is especially rare because the group tends to be well studied, she notes. For a new study in *Genes*, she and her colleagues report their finding that the pygmy loris species is actually two: a lankier species with a longer muzzle primarily found in southern Vietnam, southern Laos and Cambodia (which retains the name *Xanthonycticebus pygmaeus*) and a fuzzier, button-nosed species in northern Vietnam, northern Laos and southern China, now called *X. intermedius.*

X. intermedius was first proposed as a separate species in 1960 by zoologist Dao Van Tien, but his idea was discounted because of a specimen mix-up. Others continued to suspect two distinct species, however. In 2016, for example, a pet trader in Japan told Oxford Brookes University conservationist Anna Nekaris, who co-authored the new study, that pygmy lorises came in two types—"ugly" and "cute"—and that his customers preferred the "cute" ones.

The researchers' genetic analysis finally validated these observations. Rather than scouring the jungles for wild lorises, the team extracted DNA from 41 museum specimens in Vietnam and the U.S. Sequencing these samples showed that northern and southern pygmy lorises are distinct species whose most recent common relative lived 1.2 million years ago.

Today's lorises, cute as some are, number among few known venomous mammals; to fight, they lick special inner-elbow glands for poisonous oil that fills grooves in their teeth. Pygmy lorises were already listed as endangered, and the species split reveals a greater threat to each individual population. "The distribution of these species is much smaller than before," says Truong Nguyen, a zoologist at the Vietnam Academy of Science and Technology, who was not involved in the study. "Therefore, we have to do more to conserve them." —*Rachel Nuwer*



Chien Lee/Minden Pictures

Pygmy lorises are now split into two species.



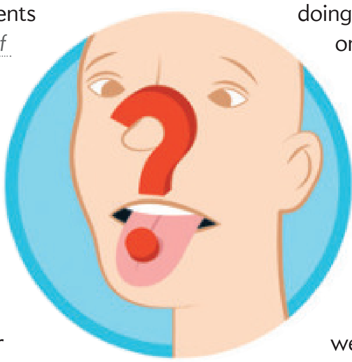
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NEUROSCIENCE

Wait, Wait … Do Tell Me!

Answers may only feel like they're on the tip of your tongue

Sometimes you know there's just the right word for something, but your brain can't find it. That frustrating feeling is called the tip-of-the-tongue (TOT) state—and for decades psychologists assumed it was caused by a partial recollection of the answer. But new research suggests this experience may be largely an illusion. Being sure you know something doesn't mean you actually do.



In a series of experiments published in the *Journal of Experimental Psychology: General*, college students attempted to answer 80 general knowledge questions with one-word answers. If they didn't provide a correct answer, they were asked if they felt like the answer was on the tip of their tongue and to provide partial information such as its first letter, its number of syllables, or what it sounded like. The team found that people in a TOT state were more likely to volunteer partial information—doing so five times as often in one experiment.

But that information tended to be wrong. Guesses at sounds and syllable counts were no more likely to be right in a TOT state than otherwise. Averaged across several experiments, first-letter guesses were only slightly more likely to match the correct answer (roughly 11 versus 8 percent). Yet participants said they thought their guess was correct 58 percent of the time while in TOT states versus 7 percent otherwise.

Previous research has shown that

GENETICS

Two Fathers

Intriguing study produces mice with two male parents

Researchers have manipulated chromosomes inside a stem cell to produce mice with two biologically male parents. Stem cell biologist Katsuhiko Hayashi of Japan's Osaka University and his team say they are the first to turn a stem cell from an adult male mouse into an egg cell. Their technique, described in *Nature*, is a variation on what scientists call in vitro gametogenesis. In this process, researchers create gametes (sperm and eggs) from induced pluripotent stem cells—unspecialized cells derived from body tissue that researchers can convert into blood cells, neurons or almost any other cell type. The successful results raise intriguing thoughts about the possibility of men someday having biological children together, but researchers emphasize that any such attempt remains a long way off.

Earlier techniques for creating egg cells began with stem cells from a female animal. But Hayashi and his group used stem cells from a male mouse instead, discarding the Y chromosome and duplicating the X chromosome. Next they embedded an altered stem cell in an artificial ovary that was also produced from stem cells; the cell eventually developed into an egg cell, or oocyte, which could then be fertilized with sperm from a male. Hayashi and his colleagues transplanted 630 embryos grown from such egg cells into surrogate female mice. This resulted in seven live pups that grew normally, Hayashi said in a recent presentation at a London gene-editing summit. One male and one female pup were tested and proved fertile as adults.

"I think it's clearly very preliminary research," says Evelyn Telfer, a reproductive biologist at the University of Edinburgh, who was not involved in the study. She says she found the work compelling and appreciates the insight it offers into how organisms reproduce. Telfer is concerned, however, by how few of the artificial egg cells grew into living mice. "Although they get quite a lot of eggs, these eggs are clearly not fully competent because they really get a very, very small proportion of them that are capable of being fertilized and forming embryos," Telfer says—and she notes that following the living pups' health and development will also be crucial. "There's a lot of work that has to be done."

Attempting the technique in people would be significantly more difficult, as Hayashi noted during his presentation. "There is a big difference between a mouse and a human," he said.

Human cells develop much more



Harvest mice

Arco/J. Fieber/Alamy Stock Photo

Illustration by Thomas Fuchs

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TOT states are not completely illusory—people better recognize correct multiple-choice answers following such states (55 versus 42 percent)—but this work joins burgeoning research indicating that we can't fully trust them. The evidence suggests that instead of partial recollection leading to a TOT state, a reverse process may be taking place: something triggers the feeling, which then motivates people to search their memories and to retrieve partial (and usually incorrect) information.

The new study "demystifies this state," says Columbia University psychologist Janet Metcalfe, whose own research has separately suggested that TOT feelings correlate with curiosity to learn the real answer. But the mechanism behind the TOT experience remains a mystery. "One possibility is that people detect familiarity with the question itself," says the study's senior author Anne Cleary, a psychologist at Colorado State University. "It may be signaling: 'something relevant is here in memory—let's do a search.'"

Cleary relates TOT to a similar state: déjà vu, which is especially common in people with certain neurological disorders such as epilepsy. In both cases, a compelling feeling of familiarity occurs, and we try to make sense of it by telling ourselves we must have seen or learned something before. Confabulation, she says, is more common than we realize.

—Matthew Hutson

slowly than mouse cells do, and scientists have honed advanced processes for artificial mouse reproduction in the laboratory, Telfer says. For human cells, these systems aren't as developed. Telfer notes that in her own work, which relies on natural precursors to human egg cells, successfully growing mature gametes remains challenging.

"I think we're at a stage where the mouse work is fabulous, but moving this area along to other species has proved to be a lot more difficult," she says. "There are challenges at every stage."

And researchers have not yet successfully produced human egg or sperm cells from stem cells, says biomedical scientist Kotaro Sasaki of the University of Pennsylvania School of Veterinary Medicine, who has worked with Hayashi in the past. "In humans, we're still so behind," Sasaki says, although he suggests that it might be technically feasible to produce human gametes one day—perhaps within a decade.

Additional research would be needed to mimic in humans the chromosome-swapping feat that sets Hayashi's new work apart. Sasaki expects that deleting Y chromosomes and duplicating X chromosomes wouldn't go nearly as smoothly in human cells. Hayashi's team used a compound that encourages chromosomal changes, and Sasaki says using the same approach in humans could cause many additional mutations, some of which could be harmful to the growing organism.

Sasaki also would like to see Hayashi's technique tested in monkey cells before those of humans—and certainly before scientists create any human embryos. He cautions that some safety issues could become apparent only in a second generation. "Using this for reproductive purposes … comes with lots and lots of ethical and legal issues, which we need to seriously address," he says.

During his presentation's Q&A, Hayashi specifically referenced only Turner syndrome (a rare infertility-associated condition in which cells that would typically contain two X chromosomes have only one) as a potential human-use case for the technique. But if it becomes viable, the process might have higher demand for facilitating childbirth for LGBTQ+ people, says Telfer, who works with people with Turner syndrome.

I. Glenn Cohen, a law professor at Harvard Law School who specializes in medical ethics, says that the new research suggests society as a whole needs to have conversations—sooner rather than later—about in vitro gametogenesis, its regulation and its ethical implications.

The way that the technique could open reproduction to couples who do not have an XX-XY chromosomal pair raises a unique question, Cohen says. "To what extent does [in vitro gametogenesis] represent the ultimate for equality for same-sex couples?" he asks. "Should this become technologically feasible for human beings, should same-sex couples have a right to do so?"

—Meghan Bartels

NEWS AROUND THE WORLD

Quick Hits

By Allison Parshall

BULGARIA, HUNGARY AND ROMANIA

The Yamnaya people, long associated with horses, are now the earliest known riders. Skeletons from around 3000 B.C.E., unearthed from burial mounds in Eastern Europe, show wear patterns consistent with "horseman syndrome," providing the oldest direct evidence of humans on horseback.

CHINA

The *Mamenchisaurus*, a massive sauropod, may have once munched treetop leaves in what is now China thanks to its 50-foot neck—possibly the longest of any known animal. Researchers estimated its neck length by comparing its fossilized vertebrae with a smaller sauropod species' skeleton.

NEPAL

Scientists found dormant *Streptococcus* and *Staphylococcus* bacteria in soil samples at an elevation of 26,000 feet on Mount Everest, probably left behind years ago by infected mountaineers. The bacteria were surprisingly resilient, reproducing once they thawed.

THAILAND

Macaques in Phang Nga Bay crack nuts with stones, breaking off and discarding sharp flakes reminiscent of early human tools, anthropologists observed. The scientists conclude that the earliest steps toward toolmaking could have arisen by accident, possibly earlier in our evolution than previously believed.

UKRAINE

Genetic analysis reveals that Chernobyl's stray dogs descended from abandoned pets living nearby when the nuclear disaster occurred there in 1986. Studying their survival in a radioactive habitat may help researchers understand how long-term radiation exposure affects humans.

U.S.

Storms sometimes cause raw sewage to spill into the ocean, and a study of San Diego's beaches showed this contamination can enter sea spray. Three quarters of bacteria found in the beaches' air came from this source, exposing even those who avoid the water.

For more details, visit www.ScientificAmerican.com/jun2023/advances

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SPACE

Science in Images

By Allison Parshall

Giant stars live fast and die young, burning through their fuel in only a few million years before sloughing off their outer layers and exploding in a dramatic supernova. Recently the James Webb Space Telescope (JWST) captured a rare image of one of these shedding giants, called a Wolf-Rayet star, in the final, fleeting stages of its life.

The star, called WR 124, is 30 times more massive than the sun but losing material quickly as it blasts hot gas into space. "We've caught it early," says Anthony Moffat, who has studied Wolf-Rayet stars for decades and was not involved in the recent JWST measurements. "This is the youngest one I know of."

Once massive stars have burned through all their hydrogen, they begin fusing helium into heavier elements. These energetic reactions push stellar winds up to millions of kilometers per hour, flinging the star's outer layers of gas into space. The burgeoning rings of gas and dust glow with the infrared radiation that JWST can detect, letting the telescope capture WR 124 in stunning new detail.

Researchers know space dust from Wolf-Rayet stars will go on to form planets and birth new stars. But it also presents a mystery: there seems to be more dust in the universe than scientists can explain by cataloging the obvious sources. "It's always an interesting place to be in science when our theories don't match our observations—and this is where we are right now with dust," says Amber Straughn, a JWST project scientist at NASA. The telescope's vivid views of a dying star's denouement, as it forges heavy elements and generates copious dust, can help scientists refine their understanding of this foundational process.

Someday WR 124 will explode in a spectacular supernova. The explosion will either leave behind a black hole or stall out as a neutron star; physicists don't have a great way to predict which with certainty. Moffat guesses it will ultimately transform into a neutron star—but we will never know for sure.

NASA, ESA, CSA, STScI, Webb ERO Production Team

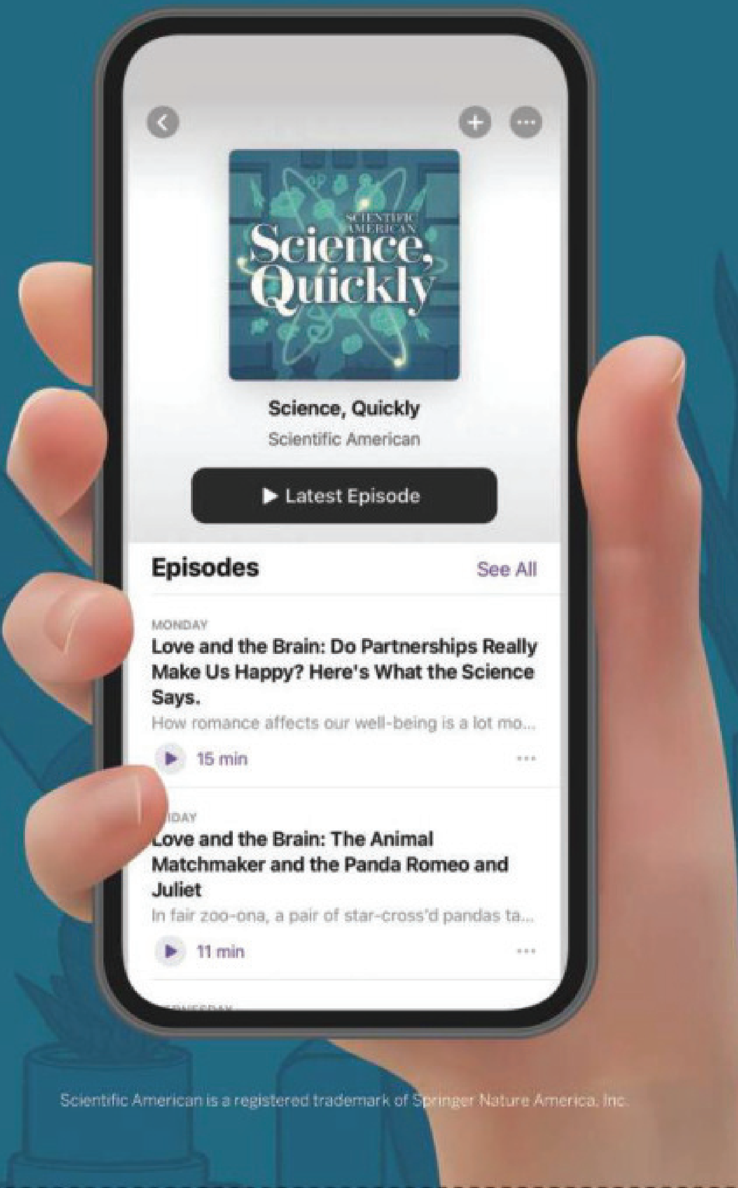
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Laura Reece Hogan is author of *Butterfly Nebula* (forthcoming in 2023 from the University of Nebraska Press), winner of the Backwaters Prize in Poetry; *Litany of Flights* (Paraclete Press, 2020), winner of the Paraclete Poetry Prize; the chapbook *O Garden-Dweller* (Finishing Line Press, 2017); and the nonfiction title *I Live, No Longer I* (Wipf & Stock, 2017).



Lyrebird

This poem wanted to rhapsodize
about the love song of the superb

lyrebird (his real name), who flares
tail and struts atop his display area, a stage

which he erects for his desired mate.
He mimics every bird (a few) of every species

(not even close) in fantastic vocalization
never before heard (true) in all of Australia

or the world—a mobbing throng of songbirds,
fricative squawks and trilling cries of panic

at the approach of a predator (frantic
wingbeats included). This poem ached

to swoon at the skill and ardor
laid at her passerine feet. But the liar

bird, it turns out, sings to deceive her
into thinking she cannot leave him because

she will be attacked instantly by a predator
(as she is), and as he mounts her, he covers

her eyes with a hood of his beating wings.

Bruce Thomson/Minden Pictures

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Lydia Denworth is an award-winning science journalist and contributing editor for *Scientific American*. She is author of *Friendship: The Evolution, Biology, and Extraordinary Power of Life's Fundamental Bond* (W. W. Norton, 2020) and several other books of popular science.

When "Good" Cholesterol Turns Bad

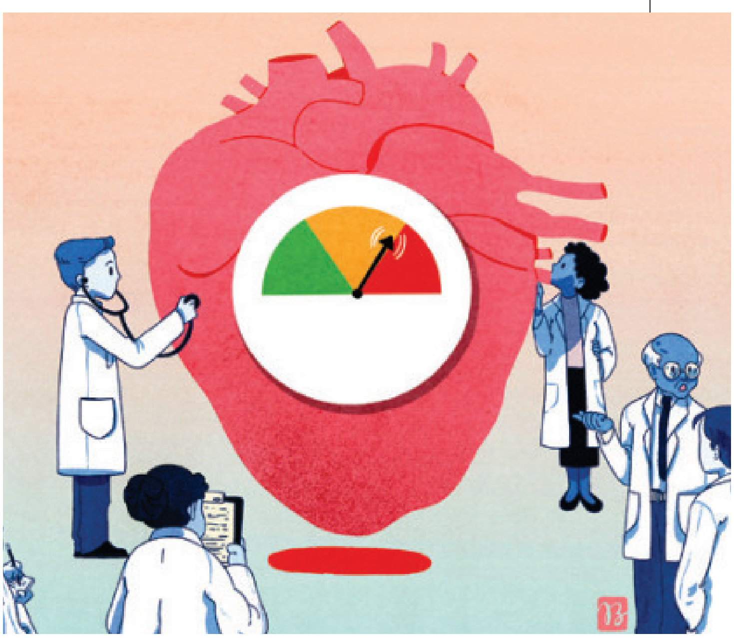
New research reveals the risks of very high HDL cholesterol levels

By Lydia Denworth

Anyone who has annual check-ups, as I do, knows that an optimal cholesterol level consists of not one number but two. Low-density lipoprotein cholesterol (LDL) should be less than 130 milligrams per deciliter (mg/dL), ideally. High-density lipoprotein cholesterol (HDL) should be more than 40 mg/dL. LDL plays the villain in this story, the "bad" cholesterol to HDL's heroic role as the "good" cholesterol.

This idea came out of the Framingham Heart Study, the pioneering research project, begun in 1948, that identified many risks for cardiovascular disease. High levels of LDL increase a person's risk of heart attacks and stroke because it builds up in artery walls and can cause atherosclerosis. HDL at higher levels, in contrast, can lower overall cholesterol levels by binding with LDL and moving it to the liver, where it is excreted as waste. A person's ratio of one type to the other type matters.

But recent research shows that the story of HDL is not so simple—more Goldilocks than Jekyll and Hyde. Those studies reveal that too little HDL is insufficient to lower LDL, but too much HDL actually heightens the risk of death. The "just right" amount of HDL lies between 40 and 80 mg/dL.



In a study of more than 400,000 people from the general population in the U.K., men with HDL levels below 40 or above 80 and women with levels above 100 were at greater risk of both mortality from all causes and cardiovascular death in particular. There were similar findings in people who already had certain risky conditions. Two smaller groups of patients with coronary artery disease and HDL levels above 80 had an alarming 96 percent higher risk of dying overall than those with lower HDL levels. And a study of more than 11,000 people with hypertension in Italy found significantly higher risk of cardiovascular events in those with HDL levels below 40 and above 80.

High levels of HDL have also been shown to affect bone density. Research on more than 16,000 Australians over the age of 70 found that those with the highest HDL levels were at a 33 percent higher risk of suffering fractures than those with lower levels.

Additional troubling evidence comes from clinical trials for drugs such as niacin that attempt to raise HDL levels on the theory that higher is better. "Those drugs were never shown to be of benefit when they were employed" along with statins, drugs that lower LDL levels, says Arshed Quyyumi, director of the Emory Clinical Cardiovascular Research Institute and a co-author of two of the recent studies.

No one knows why high levels of HDL are so harmful. "That's the million-dollar question," says cardiologist Gaetano Santulli of Albert Einstein College of Medicine, who is studying HDL. One possibility is that at higher levels, the structure of HDL molecules changes in a way that prevents them from binding tightly with circulating cholesterol to help clear the excess from the blood, Santulli says. Or it could be that at very high levels, overall amounts of cholesterol tip into the danger zone.

Fortunately, very high levels of HDL are found in less than 7 percent of the general population—one reason the risk that they carry was missed. They are more common in women but prove riskier in men, so ongoing studies are investigating the possibility that estrogen is protective.

Unfortunately, HDL levels are mostly out of individual control. They rise with exercise and with modest alcohol consumption—although heavy drinking increases total cholesterol and cardiac risk—but there appears to be little a person can do to lower them if they become excessive. We should, therefore, focus on keeping "bad" LDL levels low. Statins have been well established as reducing cardiovascular risk. In addition, a healthy lifestyle is key, says Monira Hussain, a chronic disease epidemiologist at Monash University in Melbourne, Australia, and a co-author of the bone fracture study. High-fiber, low-fat diets and increased physical activity help to lower LDL levels. Smoking is doubly harmful: it raises LDL and lowers HDL.

Cardiologists, for their part, need to change how they assess risk in their patients. "Oftentimes we go around telling people, 'Your HDL is sky-high. You're so protected,'" Quyyumi says. We now know that isn't true and that—like Goldilocks—we should all aim for the middle ground. SA

Illustration by Jay Bendt

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Two-Decade-Long Effort Has Treated 20 Million People Living with HIV

HIV is no longer a terminal diagnosis, but researchers are looking to fill gaps in treatment access to ensure help reaches all who need it

By Lauren J. Young

After 20 years a massive U.S. government effort has reached a new milestone in its battle to defang the global HIV/AIDS epidemic: this past March the Centers for Disease Control and Prevention announced that by 2022 the U.S. President's Emergency Plan for AIDS Relief (PEPFAR) had provided lifesaving antiretroviral therapy to more than 20 million people around the world with HIV—a 300-fold increase from the 66,500 people the program treated in 2004.

PEPFAR's progress has shown that halting a deadly and intimidating global epidemic isn't impossible. Since the George W. Bush administration launched the ambitious plan in 2003, PEPFAR has funneled more than $110 billion into HIV/AIDS treatment and resources. It's the largest concerted public health effort by any one nation to tackle a single disease and has been credited with changing the global course of HIV/AIDS, a devastating illness that was once considered terminal.

Illustration by David A. Johnson

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Lauren J. Young is an associate editor for health and medicine at *Scientific American.*



The year PEPFAR was announced, the World Health Organization reported an estimated 40 million people were living with HIV. Countries in sub-Saharan Africa, where the epidemic was the most severe, had the majority of cases, with an estimated 26.6 million people infected. Most of Africa's health-care facilities and universities lacked resources for the testing, drug administration and monitoring needed to care for such large numbers of patients. In many parts of the continent, HIV/AIDS simply was not a survivable disease, says Phyllis Kanki, a professor of immunology and infectious diseases at Harvard University.

"We previously have had global health problems where diseases affect all populations…. But HIV was a more dramatic scourge of a pathogen because it was killing so many people, and there was no therapy," says Kanki, who helped to start the AIDS Prevention Initiative in Nigeria in 2000 and served as principal investigator for Harvard's PEPFAR program from 2004 to 2013. "I think PEPFAR has provided the solution to what was not a livable and survivable disease for scores of people who never would have had access to [HIV drugs] in the past. I think that was the big change and why it will be heralded as a huge global health success story."

Scientific American spoke with Kanki to understand how PEPFAR helped to treat millions with HIV/AIDS, how the program could inform other worldwide health crises and what stubborn barriers remain to ending the global HIV/AIDS epidemic.

[*An edited transcript of the interview follows.*]

What was the state of the HIV/AIDS epidemic in Africa in 2003?

In many parts of Africa, they had already been describing cases in the mid- or late 1980s. It was already appreciated at that time that there were parts of the continent that were heavily burdened, such as Botswana, South Africa—those places were already documenting 20 to 25 percent infection in the general population.

I think there was a general recognition that unlike in the U.S. and Europe, where HIV infection was mainly seen in certain risk populations (and at that time it was probably intravenous drug users and men who were having sex with men), in sub-Saharan Africa, it was a much more heterosexual, young adult population. So it was harder to target who really was at risk for being infected. That was a real concern because you didn't have good programs and infrastructure set up to rapidly diagnose these people and put them on a complex therapy even if that therapy was available to you.

There was a lot of variability on the continent, but generally there weren't many accessible programs for people to receive drugs if they found out they were infected with HIV. Those with means who found out they were positive might have to pay huge sums of money to get drugs or go to Europe or the U.S. for treatment. But that was certainly just a small proportion. There were not known government programs that were readily set up to help people. And that was particularly true in places that were hardest hit and had what was already known to be the largest proportion of infected individuals.

Why was PEPFAR started?

As a minimum standard of care, you have to have a good diagnosis; you have to be able to bring in the drugs—the drugs all have to be there; you have to give the treatment to patients every month; you have to have a system so you know you're giving it to them; and then you have to have a way of monitoring them. And none of that was in place.

One of the reasons it was such a challenge for people in international health to grapple with HIV is that it was such a complicated disease. It's hard to diagnose. You can't treat somebody if you don't know they have it. Then once you put somebody on treatment, it's lifelong. At the time, patients were having to take six to 12 pills once, twice, three times a day. And it's absolutely critical that they take the pills every day because if they stopped, the viruses that are still in their bodies would become active again, and they can get sick and could die. Some pills require refrigeration. Some pills you couldn't take unless you had already eaten a meal. In some of our clinics, if populations were food-insecure, we had to provide food. And you have to monitor people with tests that most of the labs or university hospital facilities didn't have the equipment for. Who was going to pay for these tests? You couldn't ask patients to pay, and you couldn't ask labs that didn't have the equipment to run the test.

We also had problems in some populations in Africa where there was a lot of comorbidity—another disease you see with HIV is tuberculosis [TB], which a real killer all by itself. You had to deal with managing two different therapies for two different complex diseases.

Around that time, the government of Nigeria had tried to purchase generic drugs in India to provide treatment for some of the first HIV-infected individuals, recognizing it had a huge population that was already infected. They started the government program, but it was very small. Governments in Africa had already tried to begin these programs, but PEPFAR was a shot in the arm. We were able to use PEPFAR funds to really bolster what was just the beginning of Nigeria's program.

Today PEPFAR works in more than 50 countries, providing health-care infrastructure and resources—including antiretroviral therapy (ART)—to stymie the spread of HIV. What is ART, and how has it transformed HIV/AIDS care?

The virus itself enters a key cell that's important in defending your body from outside pathogens, and that cell is the lymphocyte. It's one of your white blood cells that circulates through your body and in certain organs. It's a key player in protecting you. So one of the villainous properties of the virus is that it integrates; it inserts its genetic material into yours. And that's why an infection with a retrovirus such as HIV is forever—because you can't get rid of it.

There are different classes of ART drugs that operate on different parts of the virus's life cycle. Some will basically

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stop the virus before it integrates. Other drugs inhibit the integration step. Others block the virus's entry into cells.

When we started out, we showed slides of people with two hands together with a pile of pills. Currently it's probably one pill a day—that's a single pill that includes multiple drugs. Those pills are much more effective than what we were able to give out before. So things have really changed in 20 years.

What's on the horizon for HIV/AIDS treatments?

There's PrEP (pre-exposure prophylaxis): if you're uninfected, this pill will help prevent you from being infected by another individual. There are different modalities and ways we would use these very effective therapies to try to limit spread or to decrease virus so that people don't get sick. There's a continued effort to develop a vaccine.

There's a lot of research being done on what's called the HIV cure [a few people reportedly have been cleared of HIV or considered to be in long-term remission after receiving HIV-resistant stem cells] and different ways that researchers think they can try to get rid of the disease. But certainly that's still a work in progress, I'd say.

What disparities and stigma still exist around HIV/AIDS? What efforts are there to identify those who need treatment and make sure they can access it?

There's stigma with a lot of different diseases, but we see in Africa that people don't want to be known to have HIV infection, because maybe it carries the stigma that they had multiple sex partners or had used drugs. Even just that you're not healthy—that can be a stigma in certain populations.

We've been involved with projects for men who have sex with men in Nigeria, and that's a very stigmatized population. It's very hard for them to identify and find supportive clinics, which are quasi-underground, to be able to get access to the care. That's partially because there are laws in those countries that criminalize their sexual orientation.

Africa has the largest number of kids who were infected at birth. Those kids are growing up, and many of them are stigmatized—they're 12 years old, and they've just been told by their mother that they've been taking pills, and those pills are for HIV. They don't want their classmates or other people in the community to know that's what they have because it reflects badly on them and also on their family. So then they don't want to go to the clinic and be seen. We do have problems with adolescents when they're grappling with a lot of other issues in their life and having to deal with the fact that they're supposed to go to a clinic every month that identifies them as having HIV. They're going to have to do that for the rest of their life.

"Those of us who were working in Africa at the time were kind of amazed that a U.S. program would commit so much money to people in Africa. We had never seen anything like it." —*Phyllis Kanki*

What do you think are the major next steps to reaching PEPFAR's goal of ending the HIV/AIDS epidemic as a public health threat by 2030? How realistic is it?

A lot of these international goals are kind of pies in the sky, but you have to keep going. You can't stop when you're 10 feet from the goal line. Many countries are very close to providing treatment to every person with HIV. I think Botswana, for example, is very close. It has a large infected population but has been very successful in identifying and treating all the people who are affected. And the goals to prevent infection and to treat every pregnant woman who's positive can really make a difference in getting rid of infant HIV infection because that's a starting point.

What lessons from PEPFAR could be applied to other epidemics or disease-prevention strategies?

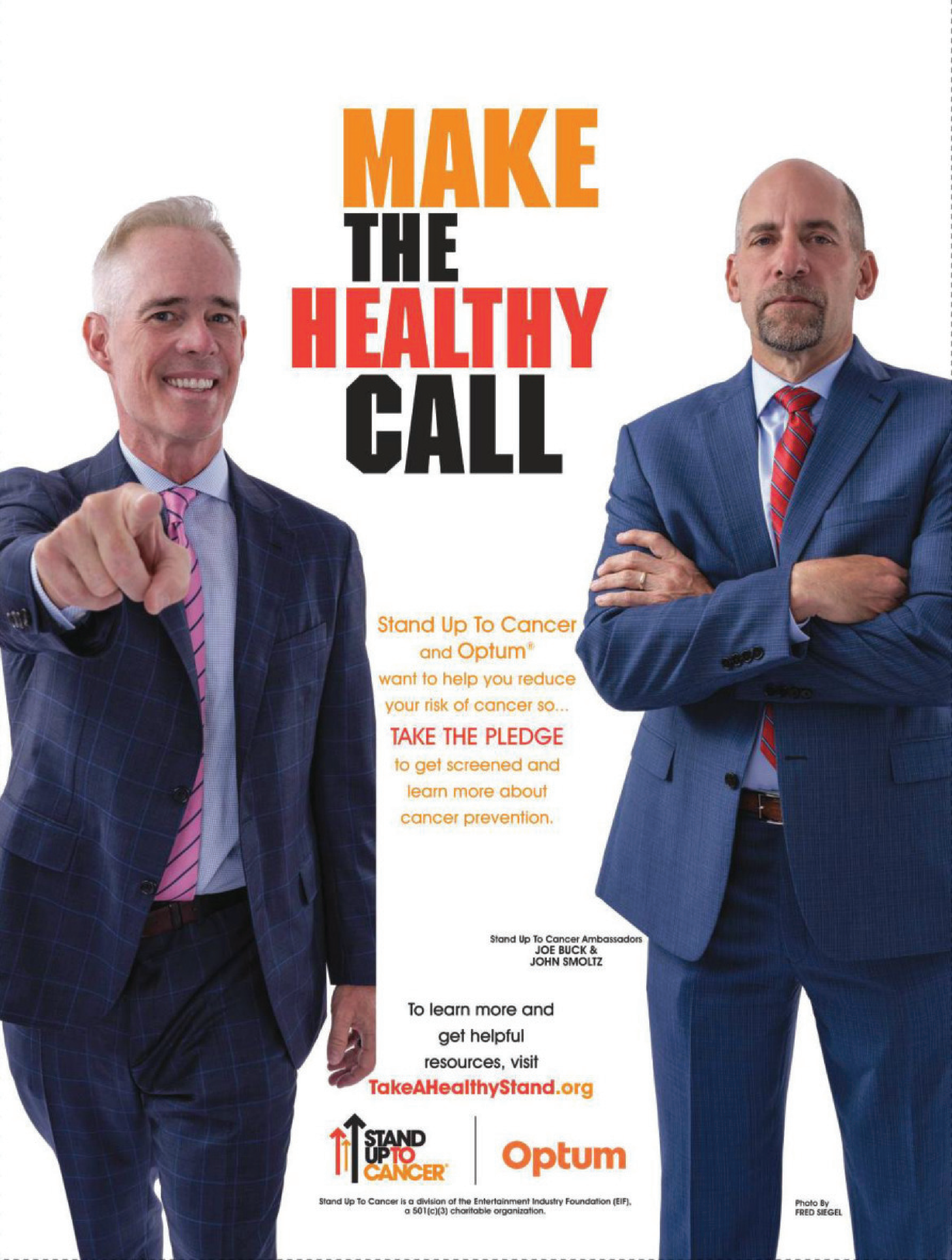
It was a brand-new approach to a global health problem. I think PEPFAR was different because it committed such a large amount of money to one disease, primarily in parts of the world that were most affected—those that were the poorest parts that would not have been able to do anything at that time with what was available. PEPFAR was really the ambulance with the medicine. The size of it and the scope of it were so huge. Those of us who were working in Africa were kind of amazed at the idea that a U.S. program would commit so much money to people in Africa. We were happy about it, of course. We had never seen anything like it. So it was really a tremendous opportunity, and no one knew whether it would really work. And 20 years later we see that it did. It really made a huge difference for health care overall, not just HIV care, in all of these countries.

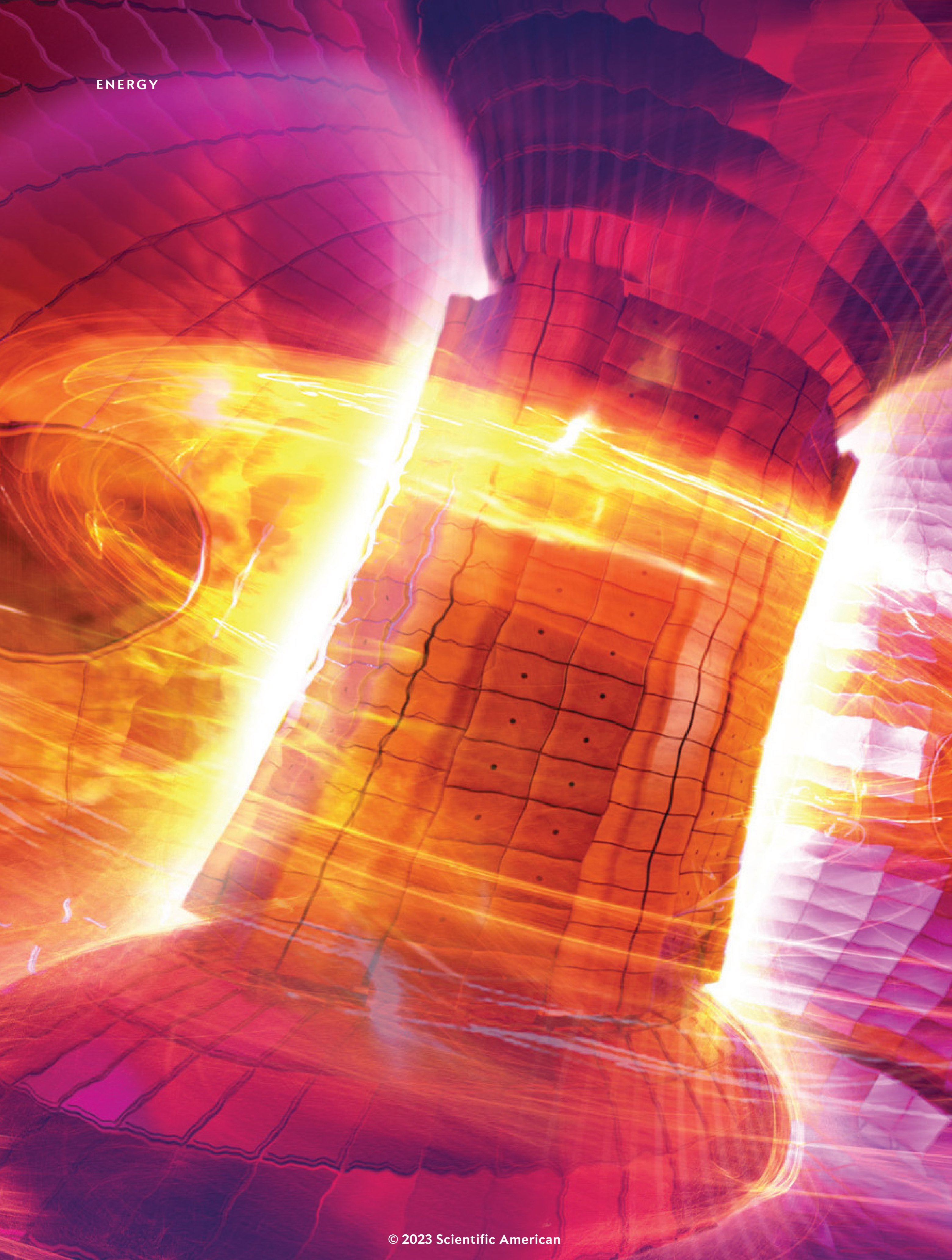
AIDS is caused by one virus, but it affects other things such as TB. So I do think the PEPFAR program provided a lot of important lessons for how we could deal with the Global TB Program. It did bolster the infrastructure that was available for TB, and it certainly improved care for that. Many of the labs that were developed for providing HIV services have been used for things such as Ebola and mpox. I think all of that has a trickle-down effect of improving health-care services overall.

And that's why I think PEPFAR will be recognized for many additional benefits that are outside of just dealing with the horrible issue of the HIV pandemic and AIDS. Many other health-care problems were addressed on the side. We're in a better position to deal with HIV than we were in 2004, for sure. SA

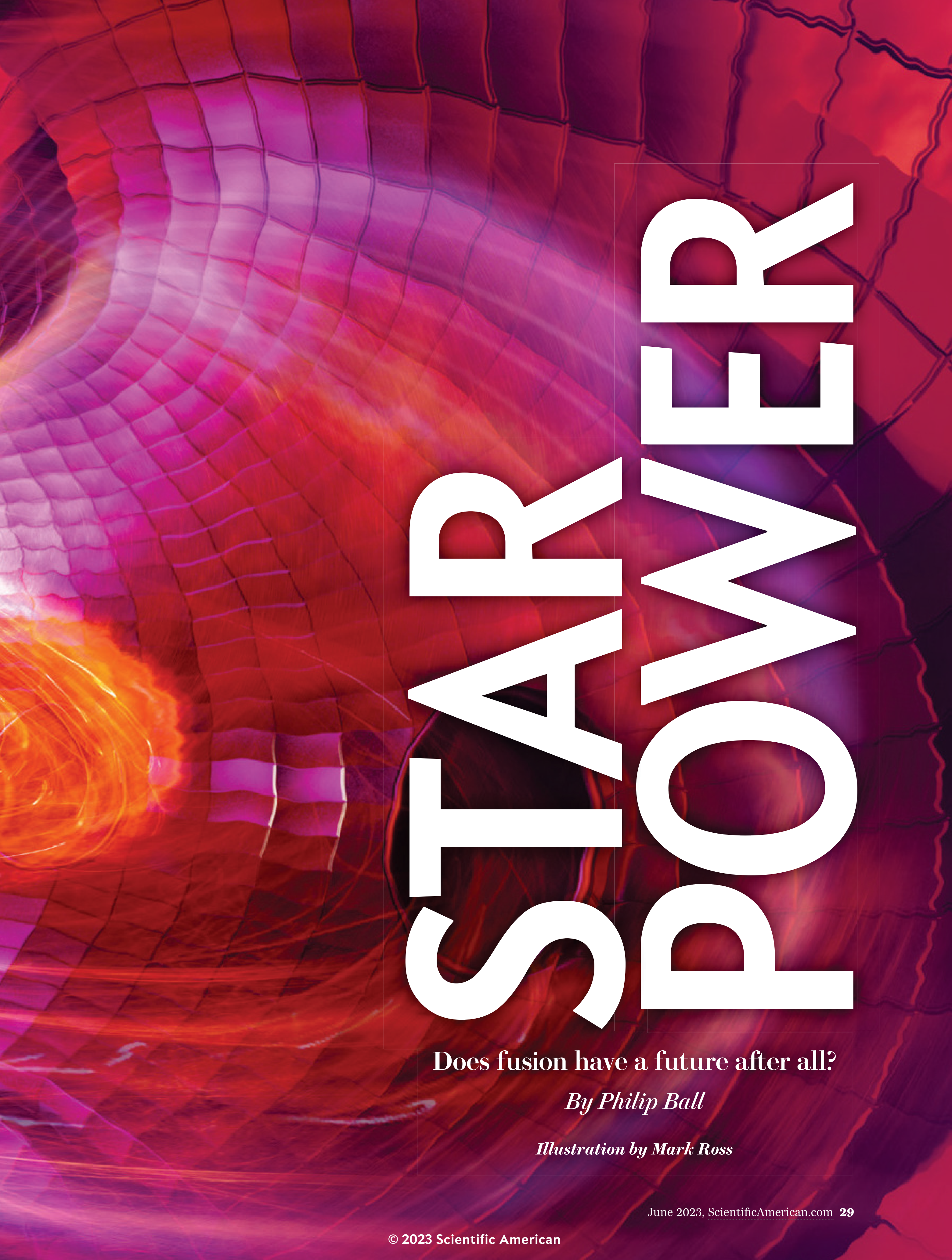
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STAR POWER

Does fusion have a future after all?

By Philip Ball

Illustration by Mark Ross

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Philip Ball is a science writer based in London. His next book, *How Life Works* (University of Chicago Press), will be published in the fall of 2023.

LAST DECEMBER PHYSICISTS WORKING ON FUSION CLAIMED A BREAKTHROUGH. A TEAM AT THE National Ignition Facility (NIF) in California announced it had extracted more energy from a controlled nuclear fusion reaction than had been used to trigger it. It was a global first and a significant step for physics—but very far from enabling practical exploitation of fusion as an energy source. The high-profile announcement elicited a familiar pattern of responses to fusion research: acclaim from boosters of the technology and dismissals from skeptics, who complain that scientists continually promise that fusion is just 20 years away (or 30 or 50, take your pick).

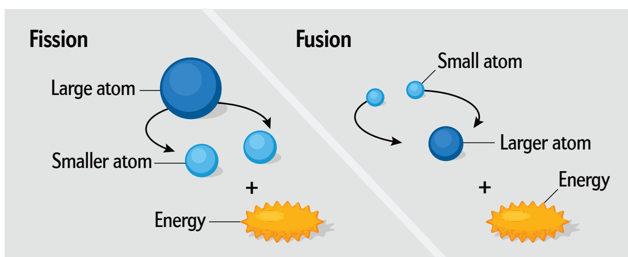
These fervent reactions reflect the high stakes for fusion. The world is increasingly desperate for an abundant source of clean energy that can mitigate the climate crisis created by burning fossil fuels. Nuclear fusion—the merging of light atomic nuclei—has the potential to produce energy with near-zero carbon emissions, without creating the dangerous radioactive waste associated with today's nuclear fission reactors, which split the very heavy nuclei of radioactive elements. Physicists have been studying fusion power since the 1950s, but turning it into a practical energy source has remained frustratingly elusive. Will it ever be a significant source of power for our energy-hungry planet—and if so, will it arrive in time to save Earth from meltdown?

The latter question is one of the few in this field to which there is a clear answer. Most experts agree that we're unlikely to be able to generate large-scale energy from nuclear fusion before around 2050 (the cautious might add on another decade). Given that the global temperature rise over the current century may be largely determined by what we do—or fail to do—about carbon emissions before then, fusion can be no savior. (Observatory columnist Naomi Oreskes also makes this point on page 86.) "I do think fusion looks a lot more plausible now than it did 10 years ago as a future energy source," says Omar Hurricane, a program leader at Lawrence Livermore National Laboratory, where the NIF is housed. "But it's not going to be viable in the next 10 to 20 years, so we need other solutions."

Decarbonizing by mid-century will therefore depend on other technologies: renewables such as solar and wind; nuclear fission; and perhaps carbon-capture techniques. As we look further out, though, there are good reasons to think fusion will be a key part of the energy economy in the second half of the century, when more developing countries will start requiring Western-size energy budgets. And solving the problem of climate change is not a one-time affair. If we can navigate the bottleneck of the next few decades without transforming the climate too radically, the road beyond may be smoother.

THE LONG HAUL

NUCLEAR FUSION was recognized as a potential source of energy almost as soon as fission was. In a debriefing meeting of the Manhattan Project in late 1945, Italian physicist Enrico Fermi, who led the project to build the first fission reactor in Chicago during World War II, envisioned fusion reactors for power generation. Scientists figured out how to release fusion energy a few years later but only in the uncontrolled Armageddon-like explosions of hydrogen bombs. Once we learned how to conduct the process in a controlled and sustained manner, some scientists predicted, electricity would become "too cheap to meter."

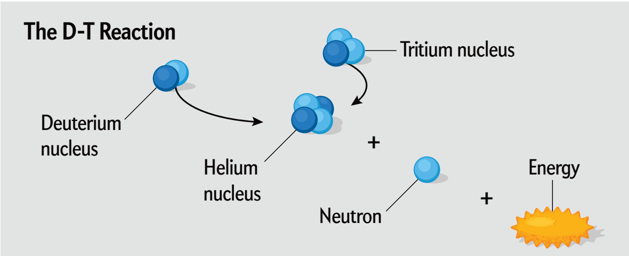


But the challenges proved much greater than expected. "It's superhard," Hurricane says. "We're basically making stars on Earth." The fusion of two hydrogen atoms to make helium is the main process that powers the sun and other stars. When such light atomic nuclei combine, they release an immense amount of energy. But because these nuclei have positive electrical charges, they repel one another, and it takes tremendous pressures and tem-

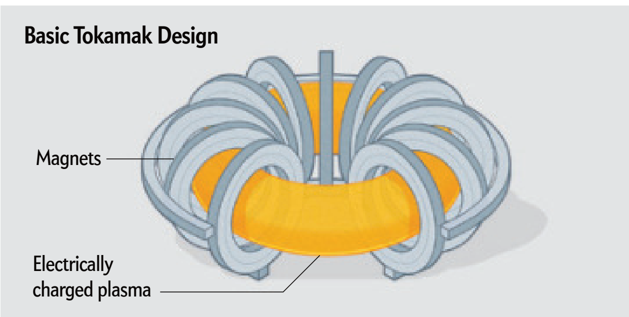
Graphics by Mark Belan

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peratures to overcome that electrostatic barrier and get them to merge. If scientists can contain the fuel for fusion—a plasma mixture of deuterium and tritium, two heavy isotopes of hydrogen—the energy released in the reaction can make it self-sustaining. But how do you bottle a plasma at a temperature of around 100 million kelvins, several times hotter than the center of the sun?



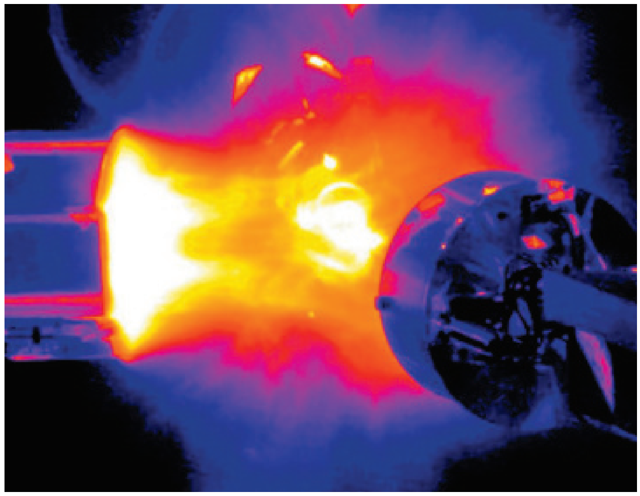
No known material can withstand such extreme conditions; they would melt even extremely heat-resistant metals such as tungsten in an instant. The answer long favored for reactor design is magnetic confinement: holding the electrically charged plasma in a "magnetic bottle" formed by strong magnetic fields so it never touches the walls of the fusion chamber. The most popular design, called a tokamak and proposed in the 1950s by Soviet scientists, uses a toroidal (or doughnut-shaped) container.



The process requires exquisite control. The furiously hot plasma won't stay still: it tends to develop large temperature gradients, which generate strong convection currents that make the plasma turbulent and hard to manage. Such instabilities, akin to miniature solar flares, can bring the plasma into contact with the walls, damaging them. Other plasma instabilities can produce beams of high-energy electrons that bore holes in the reaction-chamber cladding. Suppressing or managing these fluctuations has been one of the key challenges for tokamak designers. "The big success of the past 10 years has been in understanding this turbulence in quantitative detail," says Steven Cowley, who directs the Princeton Plasma Physics Laboratory.

One of the biggest obstacles to magnetic-confinement fusion is the need for materials that can withstand the tough treatment they'll receive from the fusing plasma. In particular, deuterium-tritium fusion makes an intense flux of high-energy neutrons, which collide with the nuclei of atoms in the metal walls and cladding, causing tiny spots of melting. The metal then recrystallizes but is weakened, with atoms shifted from their initial positions. In the cladding of a typical fusion reactor, each atom might be displaced about 100 times over the reactor's lifetime.

The consequences of such intense neutron bombardment aren't well understood, because fusion has never been sustained



PLASMA FLOWS within the target chamber at the National Ignition Facility (NIF).

Lawrence Livermore National Laboratory

for the long periods that would be required in a working reactor. "We don't know and won't know about materials degradation and lifetime until we've operated a power plant," says Ian Chapman, CEO of the U.K. Atomic Energy Authority (UKAEA), the British government's nuclear energy organization. Nevertheless, important insights into these degradation problems might be gleaned from a simple experiment that generates intense neutron beams that can be used to test materials. Such a facility—a particle-accelerator-based project called the International Fusion Materials Irradiation Facility–Demo Oriented Neutron Source—should begin operating in Granada, Spain, in the early 2030s. A similar U.S. facility called the Fusion Prototypic Neutron Source has been proposed but doesn't yet have approval.

There is still no guarantee that these material issues can be solved. If they prove insurmountable, one alternative is to make the reactor walls from liquid metal, which can't be damaged by melting and recrystallization. But that, Cowley says, brings in a whole suite of other technical concerns.

Another major challenge is making the fusion fuel. The world has abundant deuterium: this isotope constitutes 0.016 percent of natural hydrogen, so the seas are literally awash in it. But tritium forms only in small quantities naturally, and it decays radioactively with a half-life of just 12 years, so it's constantly disappearing and must be produced afresh. In principle, it can be "bred" from fusion reactions because the fusion neutrons will react with lithium to make it. Most reactor designs incorporate this breeding process by surrounding the reactor chamber with a blanket of lithium. All the same, the technology is unproven at large scales, and no one really knows whether or how well tritium production and extraction will work.

GARGANTUAN MACHINES

THE LARGEST FUSION PROJECT in the world, ITER (Latin for "the way" and originally an acronym for "International Thermonuclear Experimental Reactor") in southern France, will use a massive tokamak with a plasma radius of 6.2 meters; the entire machine will weigh 23,000 metric tons. If all goes to plan, ITER—supported by the European Union, the U.K., China, India, Japan, South Korea, Russia and the U.S.—will be the first fusion reactor to demonstrate

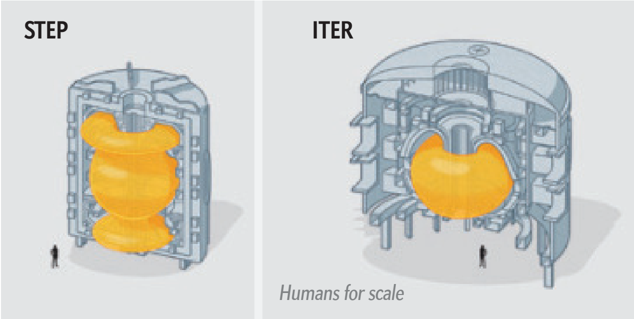
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continuous energy output at the scale of a power plant (about 500 megawatts, or MW). Construction began in 2007. The initial hope was that plasmas would be produced in the fusion chamber by about 2020, but ITER has suffered repeated delays while the estimated cost of $5.45 billion has quadrupled. This past January the project's leaders announced a further setback: the intended start of operation in 2035 may be delayed to the 2040s. ITER will not produce commercial power—as its name says, it is strictly an experimental machine intended to resolve engineering problems and prepare the way for viable power plants.

This new holdup of what some regard as a cumbersome behemoth with no guarantee of success prompted another bout of fusion skepticism. But such problems are to be expected, Hurricane says. "ITER is getting beaten up a lot, but we need to give them a break and let them sort out the problems," he says.

Chapman agrees. "It was very predictable that there would be problems, both politically and technically," he says. "The project is doing amazing things, including establishing supply chains that didn't exist before." The delay is disappointing, he admits, "but I don't think we'll look back on ITER and think it was a mistake. We'll think it was really important in the genesis of fusion. I'm convinced it will work."

Tokamaks for power plants will probably not need to be as gargantuan, and certainly cannot be as expensive, as ITER. Lately there has been increasing interest in smaller devices with a more spherical shape, like a cored apple. One of these, called the Spherical Tokamak for Energy Production (STEP), is being planned by the UKAEA as a pilot plant to be developed in parallel with ITER.



The spherical design concept had a successful proof-of-principle run with a device called the Mega Ampere Spherical Tokamak (MAST), which operated from 1999 to 2013, overseen by UKAEA and the European Atomic Energy Community (Euratom). These smaller machines have a higher energy density and thus a greater risk of heat damage, especially from the extraction of hot spent fuel in the "exhaust" system. An improved version—MAST Upgrade—turned on in 2020 and has been able to extract heat about 20 times more efficiently than the original. "That really does open the path to conceiving of a compact power plant," Chapman says.

Enter STEP, which aims to be just that: a prototype plant that produces net electricity. It is still in the concept design phase, but already the U.K. government has moved to create bespoke regulation for the project—the first in the world for fusion—that eliminates the need for a conventional nuclear license. Leaders selected a site last October: a coal power station in northern England that ceased operating in March and is scheduled to be demolished in early 2024. The site already has a cooling water supply and connections to the national grid and railway system.



Alastair Philip Wiper

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AT THE SITE of the International Thermonuclear Experimental Reactor (ITER), a poloidal field coil undergoes testing. Six of these ring-shaped magnets will steer plasma within the experiment.

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The E.U. is planning its own prototype plant, called the DEMOnstration Power Plant (DEMO), administered by the EUROfusion consortium. The project was originally intended as a 500-MW plant, but last year technical uncertainties arising from the ITER delays led the consortium to scale back the goal to around 200 MW. Construction might begin in the early 2040s, says Tony Donné, EUROfusion's program manager. "I'm convinced we can build such a device in 10 years."

Donné adds that there are equivalent "stepping stone" projects toward fusion plants in South Korea, Japan and China; the U.S. made plans for a smaller device called the Fusion Nuclear Science Facility. "China has come to the party a bit late but is now investing heavily and growing its workforce rapidly," Chapman says. "It is definitely catching up with what already exists in Europe and the U.S." Donné believes that some friendly competition—a kind of "moon race" for the first prototype fusion plant—could be beneficial as long as countries continue to share information.

THE START-UP SCENE

IT'S NOT ALL ABOUT big national and international projects. Small spherical tokamaks are one of the technologies that have brought fusion within the reach of private companies. Several dozen fusion start-ups have sprung up around the world, such as Commonwealth Fusion Systems (CFS) in Massachusetts, General Fusion in Canada, and Tokamak Energy in the U.K.

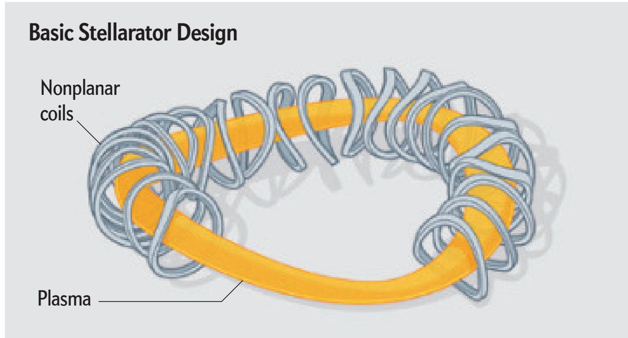
General Fusion, with support from the UKAEA, has just begun building a demonstration plant that it hopes (ambitiously) to have running by 2025. According to the company's former CEO Christofer Mowry, it will be "the first power-plant-relevant large-scale demonstration." Meanwhile CFS, in partnership with the Plasma Science and Fusion Center (PSFC) of the Massachusetts Institute of Technology and others, is building a prototype device called SPARC, also targeted for completion in 2025. SPARC will be a midsize tokamak in which the plasma is tightly confined by very intense magnetic fields produced by new high-temperature superconducting magnets developed at M.I.T. and unveiled in 2021. Such magnets were hailed as a significant step for magnetic-confinement fusion because the power density in the plasma increases rapidly as the strength of the magnetic field rises.

The SPARC team aims to extract net energy from the plasma (about 10 times more energy out than in) and to generate 50 to 140 MW of fusion power. Although SPARC is much smaller than ITER, the PSFC's director, Dennis Whyte, says its mission is similar: to solve the science and technology problems that stand in the way of commercialization. It won't feed any energy into the grid, but it's meant to clear a path for the "affordable, robust, compact" fusion reactor concept developed at M.I.T. and pursued by CFS, which Cowley considers "the most impactful company" so far.

Cowley welcomes such projects but cautions against seeing them as a shortcut to making fusion a realistic energy source. "We see these start-up companies coming in with a lot of enthusiasm, and a lot of their focus is on a particular part of the problem," he says. It's highly unlikely that one of them will make fusion energy commercial before the big guns, and many will simply fold—as some start-ups always do. But Chapman believes others will become valuable suppliers of expertise and of specialized components such as magnets. "Most of the small fusion companies will end up being part of the supply chain," he says.

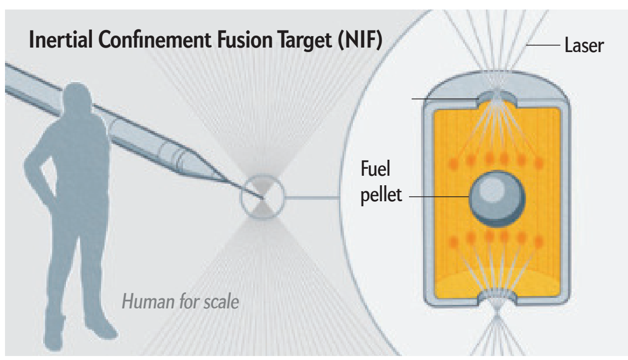
DIFFERENT DESIGNS

SETUPS FOR MAGNETIC-CONFINEMENT fusion are not necessarily limited to tokamaks. In the 1950s astrophysicist Lyman Spitzer argued that plasma might be contained more effectively in a doughnut chamber with a twisted tunnel wall. With this configuration, the device could keep the plasma constrained by using the magnetic fields generated by flows in the charged plasma itself.



The more complex geometry of this design, called a stellarator, is tricky to engineer, but a few projects are pursuing it. A notable example is the Wendelstein 7-X stellarator in Greifswald, Germany, completed in 2015 and now operating again after a three-year upgrade. "A stellarator has some advantages, but technically it's a more complicated device," Donné says. "In Europe, we're working on the stellarator as a backup to the tokamak." The technology is still at a relatively early stage, so if that backup turns out to be essential, the timescale for practical fusion is likely to be pushed back again.

The strategy at the NIF is totally different from all of these projects. Instead of using a large amount of plasma confined by magnetic fields, the NIF experiment ignites a tiny target of deuterium and tritium. In this case, the fusing plasma is held in place only fleetingly by its own inertia after the experiment triggers fusion by squeezing the fuel abruptly and heating it intensely—a scheme called inertial confinement fusion. The NIF produces these extreme conditions by focusing very intense laser beams on the pellet-shaped targets. The fusion energy is released in a brief burst before the hot plasma expands. This kind of energy production would therefore happen in pulses, and fuel capsules would have to be constantly moved one after another into the reaction chamber to be ignited. Most researchers estimate that for the approach to be practical, capsules would have to be replaced about 10 times a second.

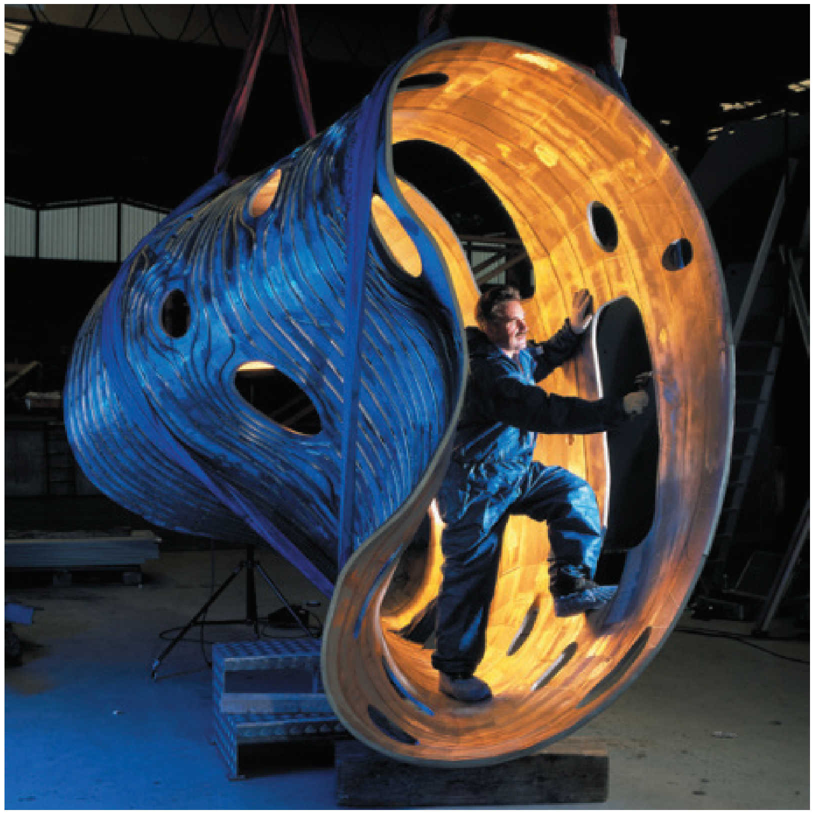


The challenges for inertial confinement fusion are daunting, and at present only a few facilities in the world are studying it.

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Besides the NIF, the biggest, there are the Megajoule Laser facility in France and the Shenguang-III laser facility in China; Russia also might be pursuing this approach, but the details are hard to ascertain. Energy generation isn't actually a main part of the NIF mission; the facility was intended mostly to trigger nuclear reactions for studying and maintaining the U.S. stockpile of nuclear weapons. "The primary work at the NIF has been funded entirely by the U.S. national security apparatus," Hurricane says. "It is not a fusion reactor and is not meant to demonstrate fusion energy in any practical sense."

Much more work lies ahead to make inertial confinement fusion a true contender for supplying energy. "The work has focused on the fundamental science, and we haven't put as much effort into the supporting technologies needed for a power plant," says Tammy Ma, who leads the NIF's inertial fusion energy initiative.



A SEGMENT of the twisted vessel for plasma at the Wendelstein 7-X stellarator fusion experiment.

Wolfgang Filser/MPI for Plasma Physics

LOOKING FORWARD

GIVEN THIS VARIED LANDSCAPE of fusion projects, how close is practical fusion energy really? Chapman is blunt: "There is not today a single project underway to build a fusion power plant that will produce energy."

And real power plants—ones that aren't just prototypes—take a decade or so to construct. "Experiments are making progress, and the progress is impressive," Chapman says, "but fusion is not going to be working [as a source of mass energy] in a few years' time." Donné is blunter still: "Anyone who tells me that they'll have a working future reactor in five or 10 years is either completely ignorant or a liar."

Forecasting when fusion energy will arrive has always been a risky business, but experts now mostly agree on the approximate timescales. "Suppose we get a pilot plant that works by the end of the 2030s, although that would be going some," Cowley says. Such a plant is unlikely to be a blueprint for commercialization, and so, he says, "I think you'd have another stage of about 10 years from a pilot plant to the first commercial reactor." Chapman concurs that fusion plants might be feeding power into the grid by around 2050 and then could become steadily more important to the energy economy in the second half of the century, especially post-2060.

Fusion plants are likely to be of about the same scale as today's fossil-fuel or fission plants, with outputs of a few gigawatts. That means they could be constructed on the same sites, replacing like with like, and with all the necessary electrical-grid infrastructure already in place. "You could say that fusion is very easy to plug in and replace either fossil fuels or fission," Donné says. "This can be a very smooth transition." He expects that fusion plants will replace first the still active coal plants, then oil and gas, and finally fission.

Even if fusion can't save us from the immediate climate crisis, over the long term it may be the best option to satisfy our energy needs without destroying the planet. Soviet fusion visionary Lev Artsimovich, the "father of the tokamak," once said that the world will have nuclear fusion when it decides it needs it. "When we realize what climate change will do as an existential threat, the delivery of fusion will accelerate enormously," Chapman says, drawing an analogy to the quick development of COVID-19 vaccines. At the moment we simply have no other long-term way of getting to net-zero carbon emissions, especially because the global energy demand is projected to triple between 2050 and 2100. "Fusion is essential" to meet that need, Chapman says. "I can't see what else it will be." Renewables such as wind and solar energy definitely have a role to play, Donné says, but they aren't likely to be enough.

Building a new kind of energy infrastructure from the ground up presents opportunities as well as challenges. Nuclear fission planners made some serious mistakes in terms of design and public relations, but now the nascent fusion industry has a chance to learn from those mistakes and do better—not least by thinking about issues of energy equity and justice. "When we have these plants, where do we place them so that we can provide a clean energy source for all types of communities?" the NIF's Ma asks. "How do we build up a workforce that is diverse? How do we ensure that as we are building up this industry, we are training folks to have the skills of the future? We get to at least try to do it right this time." SA

FROM OUR ARCHIVES

Fusion Dreams. Clara Moskowitz; December 2020.

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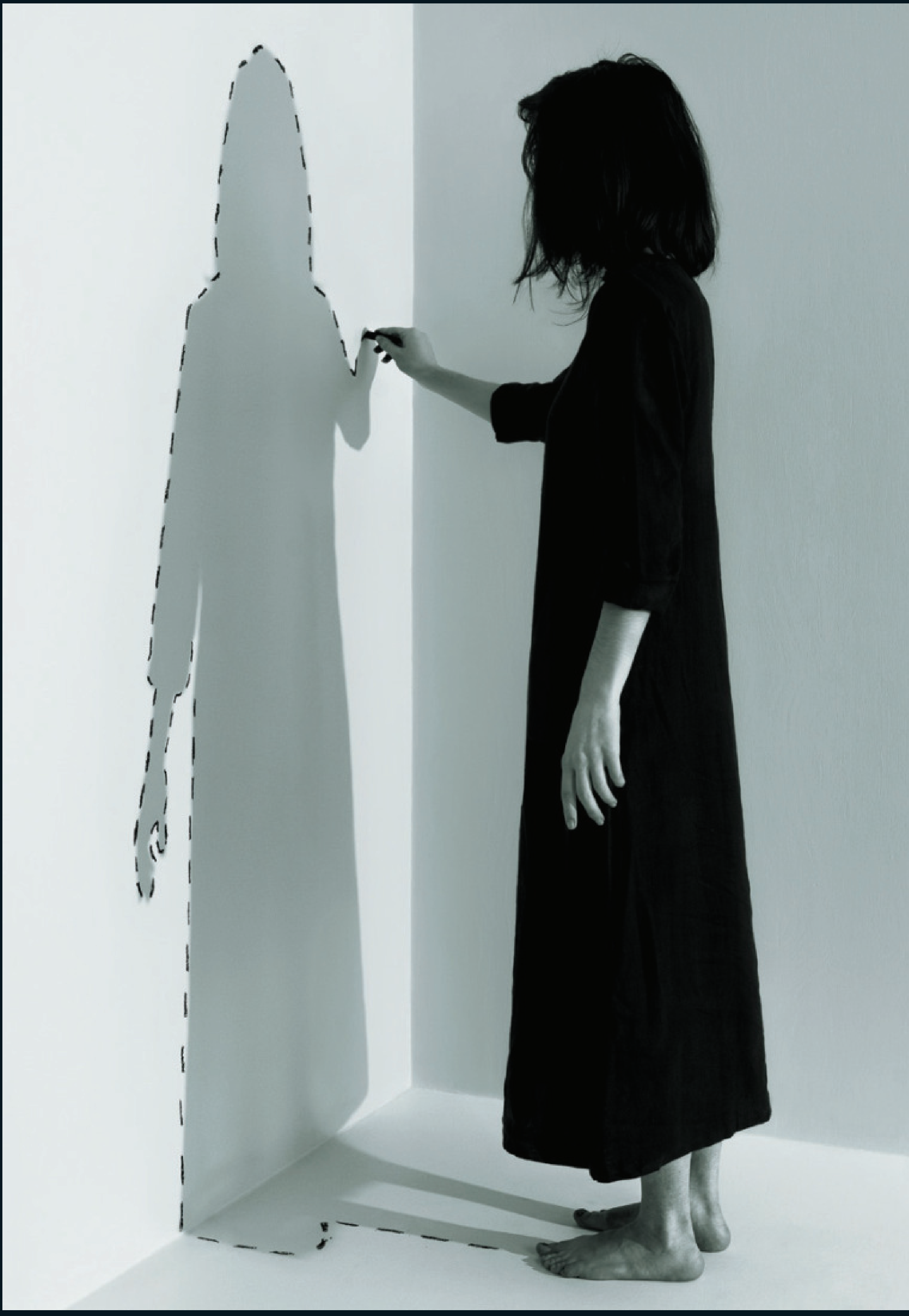
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the community of ella

A young woman with multiple personalities gets better without losing her "parts." Instead they learn to work as a team

By Rebecca J. Lester

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Rebecca J. Lester is chair of the anthropology department at Washington University in St. Louis, a licensed clinical social worker specializing in trauma and eating disorders, and a past president of the Society for Psychological Anthropology. She is author of *Famished: Eating Disorders and Failed Care in America* (University of California Press, 2019).



WHEN ELLA TIME TRAVELED IN MY OFFICE FOR THE FIRST TIME, I did not realize what was happening right away. She was sitting comfortably in a chair, her hands folded, her back straight and her feet flat on the floor. There was no dramatic change, no shuddering or twitching. But then I saw it: a slight shift in how she held her body. Her face softened almost imperceptibly. I heard it, too: her voice sounded different, pitched just a teeny bit higher than usual, with a new singsong quality. At first I found it curious. As it continued, I felt a growing sense of unease. Acting on a hunch, I asked her how old she was. "I'm seven," she said. Ella was 19.

I'm a licensed clinical social worker specializing in trauma, eating disorders, self-harm, personality disorders, and gender and sexuality issues. I am also a cultural anthropologist with expertise in the intersections of culture and mental health. Ella (I have changed her name here to protect her privacy) was referred to me by a concerned university colleague who taught her in one of her classes. Ella and I began meeting for twice-weekly therapy sessions, which eventually increased to three times a week. We worked together for four and a half years.

Ella came for help with complex post-traumatic stress disorder. She was a survivor of long-term, severe childhood sexual abuse by a trusted religious leader. She had nightmares, flashbacks and anxiety, and she engaged in various forms of self-harm, among other symptoms. But there were other things going on. Ella regularly missed pockets of time. She "spaced out" unexpectedly, "waking up" wearing different clothes. She experienced intense thoughts, emotions and urges that felt like they were coming from someone other than herself.

In a way, they were. Ella, it eventually became clear, had dissociative identity disorder (DID), a clinical condition in which a person has two or more distinct personalities that regularly take control of the person's behavior, as well as recurring periods of amnesia. Popularly known as "split" or multiple personalities, DID and its criteria are listed in the *Diagnostic and Statistical Manual of Mental Disorders* (*DSM-5*), the authoritative psychiatric compendium published by the American Psychiatric Association. Over time Ella manifested 12 different personalities (or "parts" as she called them) ranging in age from two to 16. Each part had a different name; her own memories and experiences; and distinctive speech patterns, mannerisms and handwriting. Some communicated in words, and others were silent, conveying things through drawings or using stuffed animals to enact scenes. Most of the time the different parts were not aware of what was happening when another part was "out," making for a fragmented and confusing existence.

DID is a highly controversial diagnosis. Patients with DID symptoms are frequently dismissed by clinicians and laypeople alike as faking or neurotic, or both. This kind of skepticism has been fueled by the case of "Sybil," who became the subject of a 1973 best-selling book; later evidence indicated she was faking her condition. My diagnosis of Ella was based on the *DSM-5* criteria, her score on various psychological tests of dissociation, and our years of working together. Notably, fakes have something to gain by faking. Ella had nothing but losses. Her personalities would sabotage one another, ruining relationships and threatening her school performance.

So how to help her? Therapists have traditionally treated people with DID with the goal of "integrating" them: bringing the fragmented parts back together into

John Dykstra (*preceding pages*)

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one core self. This is still the most common approach, and it reflects a Western view of the world in which one body can have only one identity.

This is not a universal human belief, however. People in many other cultures see the body as host to several identities. Given my anthropological training, I approached Ella's DID symptoms differently than many clinicians might. Ella looked to me like a *community*—a dysfunctional one at that moment but a community, nonetheless. My concern was less with the number of selves she had than with how those selves worked together—or not—in her daily life. Was it possible to bring those selves into a harmonious coexistence? Ella thought it was, and so did I, so that was the mission we embarked on in therapy.

ELLA DIDN'T SHOW UP TALKING ABOUT "PARTS." WE STARTED our therapy focused on helping her manage the everyday consequences of the abuse she had endured. Then, about a year after we began, things took an unexpected turn. Ella came into her session one day clutching several scraps of paper covered in childlike writing: shaky words with misshapen letters and misspellings. Some of the notes were written backward. "I keep finding these scattered around my room," she told me, alarmed. "I've also found these," she said, pulling drawings of stick figures, animals and rainbows out of her backpack, some with smiley-face stickers on them. Despite the overtly innocent tone of these materials, Ella found them frightening. She had no idea where they had come from. "I don't understand what's happening," she told me. "I must be making them, right? But I don't remember doing it."

As our sessions continued, Ella recounted more strange incidents. She would sometimes "wake up" in the middle of a conversation with someone and realize she was somewhere other than the place in which she last remembered being. Occasionally she would find things moved around in her room she didn't remember moving. I began receiving e-mails sent from her address consisting of strings of consonants with no vowels at all, like this:

Htsmmscrdrtnwwshwrhrblktshrndmksmflsf

These were decipherable with some effort (this one says, "Hi, it's me. I'm scared right now. Wish [you?] were here. Blanket is here and makes me feel safe"), but Ella had no memory of sending them.

That unnerving first time the seven-year-old appeared in front of me happened when Ella and I had been working together for about 13 months. After that, Ella began to dissociate into younger parts more often during therapy. Some of her parts came out in full flashback mode, feeling absolutely terrified, and had to be talked down. Other parts were silent or angry. The seven-year-old and I would sit on the floor and color or make art while we talked, sometimes about what was happening in Ella's current life, sometimes about things that had happened in the past. To distinguish among her identities, Ella asked them to use different-colored markers when they wrote or drew. The seven-year-old part chose purple as her color and as her name: Violet.

As far as Ella could discern, all these parts were versions of her at different ages. Some parts were better at dealing with certain situations and feelings than others were, and they would "come out" when those feelings were especially strong or when a situation required that part to appear and act.

Sometimes, however, the parts were in conflict. For example, a part named Ada—age 16—first appeared in the wake of a catastrophic rejection by a high school guidance counselor after Ella shared her abuse history. As a result, Ada was mistrusting and suspicious. She was also extremely rigid, moralistic and self-punishing and was quick to lash out with an acerbic tongue, including at me. She viewed herself as a protector. Violet was very different. Violet trusted easily and loved generously. She really wanted to connect with other people. These traits often put Violet and Ada at odds and sometimes led to all-out internal warfare, with Ada, the older and stronger, usually prevailing. To punish Violet, Ada would sometimes hurt "the body" by hitting and biting her arms and legs and holding a pillow over her face until she passed out, behaviors Violet experienced as a reenactment of the abuse that created her.

Over time Ella showed 12 different personalities ranging in age from two to 16.

PSYCHIATRISTS BELIEVE THAT DEVELOPING MULTIPLE IDENTITIES protects a child—the disorder usually has roots in childhood—by keeping traumatic memories and emotions contained within specific identities rather than letting them overwhelm the child completely.

This is a contemporary understanding of DID, but people have speculated for centuries about what might cause someone to exhibit what appear to be multiple personalities (the first reliable recorded case of what we now call DID was noted in a young nun named Jeanne Fery in 1584 in Mons, France, and was regarded as a spiritual affliction). Today DID is one of several dissociative disorders outlined in the *DSM-5*. It is well documented and is not as rare as many people think: community-based studies from around the globe consistently find DID present in about 1 to 1.5 percent of the population.

Despite these findings, many Western clinicians do not believe that DID exists, attributing it instead to misdiagnosis or fabrication and pointing to the lack of definitive biomedical evidence for the condition. No blood test or x-ray can help us identify it, for example, and none of the standard biomedical mechanisms of evidence apply. (It is interesting that there is no biological test for schizophrenia, either, yet few people doubt that the disease exists or that people's hallucinations are genuine. The assumption of "one self in one body" isn't challenged by

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VIOLET, age seven and one of Ella's personalities, drew this picture of all the "parts" holding hands, with therapist Rebecca J. Lester in the center. (Text was removed from the drawing to protect privacy.)

Ella

schizophrenia, but it is by DID.) Although brain scans show different brain structures and functions in people with DID, it is not clear whether these differences are the cause or the result of dissociation.

Another confounding possibility is diagnostic overreach and unconscious bias on the part of therapists. Despite the ambiguity of DID's presentation, striking similarities among patients who receive the diagnosis are notable. Like other dissociative disorders, DID is diagnosed primarily in young adult women, many with a reported history of severe child abuse, especially sexual abuse. This profile may indicate something about the origins of DID, but it also might reflect the way clinicians tend to label certain types of psychiatric distress in younger women. Studies have shown stark gender and race differences in diagnoses of psychiatric conditions, even among patients with the same reported symptoms. It's therefore possible that a clinician might see and diagnose DID because the client fits an expected profile.

Correctly diagnosing DID is tricky. To make an accurate diagnosis, a clinician must carefully assess the totality of a person's symptoms and rule out other possible causes for the appearance of multiple personalities, as well as the chance of a fake. This evaluation requires time and expertise. In addition to assessing whether a client meets the official diagnostic criteria, a therapist must also consider whether the specifics of the different personalities hold up across sessions over time, whether any inconsistencies suggest the presentation might be fabricated, what kind of affect is associated with or evoked by the appearance of different personalities, whether the client seems to get some secondary benefit from displaying DID symptoms—Sybil's doctor paid her apartment rent, for instance—and what role the diagnosis plays in their everyday life and their understanding of themselves.

BEFORE WORKING WITH ELLA, I WAS AGNOSTIC ABOUT DID. I knew about the history of the diagnosis and the criticism lodged against it. I knew about factitious disorder (in which a patient makes up or deliberately induces symptoms) and malingering; about trauma, self-harm, disordered eating and dissociation; and about the careful work needed to accurately assess and diagnose any client, especially one who presents with symptoms that are complex or ambiguous. For these reasons, I did not

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jump to conclusions about Ella's condition. I took time—many months—to carefully assess what I was hearing in sessions and perceiving through metacommunicative cues such as body language, eye contact, posture, vocal quality and communication style. In addition to our 50-minute, three-times-a-week sessions, Ella also corresponded with me regularly by e-mail, with different parts e-mailing me (and sometimes one another) almost daily. I had no shortage of data to work with, then, in assessing Ella's condition. I kept detailed notes on our sessions and remained especially vigilant for any inconsistencies or other indications that Ella's parts were fabricated.

Over time I became persuaded that Ella's parts were indeed "real" in the sense that her discontinuities in consciousness and awareness led her to experience aspects of herself as separate personalities. I don't think she was faking her symptoms or performing what she thought I wanted or expected to see. It's possible that she was, but throughout our years of working together, I saw absolutely no indicators of it. Nor did Ella seem to take any pleasure in having parts; on the contrary, it made her life exceedingly difficult, especially in the beginning, and she often expressed significant frustration at her situation.

The next step was figuring out how to help this extremely distressed and traumatized woman. Here my anthropological training came in alongside my work as a therapist. What, I wondered, might happen if we took the "is she or isn't she?" question off the table and instead questioned our own assumptions about what makes a healthy self?

In the contemporary West, we generally think of the self as a bounded, unique, more or less integrated center of emotional awareness, judgment and action that is distinct from other selves and from the world around us. This self is singular, personal, intimate and private: it is not directly accessible to anyone but us. The self is the core of a person, the center of experience, the fundamental aspect of us that makes us who we are.

So foundational is this concept of the self to Western culture that it operates like a natural fact. It seems so self-evident that it serves as the basis of our understanding of mental health and illness. Almost every disorder outlined in the *DSM-5* describes a deviation from the idealized notion of what a self is and does. "Self-disturbances" characterize conditions such as psychosis, depersonalization, borderline personality disorder, codependency, eating disorders and dissociation, among many others. Our cultural understanding of "self," then, largely determines how we define mental illness and health.

But this understanding of the self is far from universal. Anthropologists have long documented very different ideas about the self in cultures around the world; indeed, the possibility of more than one entity residing in a body at a time is a widespread human belief. In parts of central Africa, for example, people assert that a child receives a number of different souls at birth: one from the mother's clan, one from the father's clan, and others from elsewhere. The Jívaro people of Ecuador posit the existence of three souls, each imbued with unique potential. The Dahomey, also called the Fon, in West Africa traditionally believed that women had three souls and men had four. The Fang, who live in Cameroon, Equatorial Guinea and Gabon, believe in seven souls, each governing different aspects of the person. A number of North American Indigenous communities believe some individuals are "two-spirited," having one spirit that is female and one that is male. Some interpretations of Jewish religious texts contend that up to four souls can be reincarnated in one body. Cultures all over the world also recognize spirit possession, in which an individual serves as host to a supernatural entity.

Such views are not confined to distant lands, either. Anthropologist Thomas J. Csordas has described how some American evangelical Christians understand the presence and active participation of multiple demons and spirits within their bodies.

Dramatic accounts aside, having multiple parts, whatever we call them—entities, selves, souls—is a more mundane state than most people might think. Neuroscientist David Eagleman has described how the brain's complex system operates as a collection of individual "minds" that together produce the illusion of unified consciousness. Internal Family Systems therapy, a burgeoning evidence-based approach, posits that the mind is inherently multiple—that what we experience as "self" is really an internal system of subjectivities that shift in response to inner and outer cues and that can be engaged and transformed through therapy.

In other words, we *all* have parts. We even regularly talk about them without marking it as odd. As I'm writing this article, part of me is excited to share what I've learned. Another part of me is overwhelmed by other work and is mindful of all the things not getting done while I write. Another part is nervous about how my ideas—and Ella—will be received. Yet another part is eager for the engagement. That I have all these different parts of me operating at once probably doesn't raise any alarms: we are all familiar with these kinds of complexities. In this sense, I don't think Ella is that different from the rest of us, except that she has barriers between her parts that disrupt the sense of continuous consciousness most of us take for granted.

ELLA WAS A YOUNG WOMAN IN TROUBLE, CERTAINLY, BUT FROM my anthropological perspective, she also began to look like a *community of selves* within one individual. Anthropologists have ample tools for engaging with and understanding communities: we go to them, we listen to people living in them, we watch how they live and interact, and we learn.

But Ella's internal world was unlike any other community I had encountered. Most communities are composed of multiple bodies sharing the same temporal location. In Ella's case, the community consisted of one body and multiple temporal locations. Some parts

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existed only in the past, continually living and reliving their original traumas. Others lived almost entirely in the present, aware of when they were "made" but then going offline until they came out again years later, with few memories of what had happened while they were not in the foreground. Violet was special. She was created when the body was seven, and she had memories of the original abuse, but unlike other parts, she had remained largely present in the background of Ella's life between then and now and knew what had happened during the intervening years. With her unique perspective on Ella's internal world across time, Violet became my "key informant" in an anthropological sense as I explored Ella's community of parts.

Psychiatrist Irvin D. Yalom has said that one must create a new therapy for each client because each person's internal meaning system is different, and so each will have distinct ways of experiencing basic existential concerns. Building on Yalom's concept, we might say that each person's inner world is a unique *culture* with its own history, language, values, practices and symbolic systems. Approaching therapy in this way requires an anthropologically informed exploration of the client's inner world. Such work takes time and patience and is built on a foundation of trust. Like an anthropologist, a therapist must learn to speak the local language of the client's inner culture and understand the symbolic systems, ritual practices and dominant themes that reverberate in different ways in different domains. Most of all, therapists must remember that we are guests and that however much training and knowledge we may have, we can never truly know what it is like to live with that particular inner reality. The client is the true expert on her own experience. I took this approach to my work with Ella.

AS I PROCEEDED IN MY "FIELDWORK" WITH ELLA'S INTERNAL community, my earlier anthropological research in a very different context became relevant. In a book I wrote about young women entering a Roman Catholic convent in Mexico, I argued that new initiates (called postulants) came to understand their religious vocations by developing a new experience of time: they learned to read the self simultaneously across different temporal scales, one based on the everyday world and one based on the eternal time of God and creation.

The postulants are guided in reconceptualizing their entire lives as a series of events indicating a divinely directed transformation, a progressive unfolding of self that operates in both temporal registers. For example, during their first week in the convent, the postulants learned that the homesickness they were feeling was a replay of the feelings the Virgin Mary had when she left home to travel to Jerusalem. In a retreat focused on the Virgin Mary held one month before the group was to enter the novitiate, the Mistress of Postulants told them that the 10 months of the postulancy are like the months of pregnancy—that the postulants were, in a very real spiritual sense, gestating Jesus in their wombs. They became, in other words, simultaneously the daughters, brides and mothers of Christ, orienting toward a spiritual rather than a physical model of female reproduction. Learning to construct a meaningful narrative of self that embraced—rather than denied—such temporal paradoxes sat at the heart of the transformation the postulants underwent in their first year.

I saw something similar in Ella in that different parts existed at different times yet also in the present. This trait formed what Ella and I came to call a telescoping process, with parts stretching back across time, marking the discontinuity between past and present, and then collapsing it. Although some parts remained the age the body was when they were made, parts of any age could be created at any time. Once, for example, a new part showed up who was about two years old and communicated only by crying and demanding ice cream at the grocery store. In addition to telescoping time, then, identities could actively use temporal displacement in their communication. If I had not done the work at the convent or known about the anthropological research on varieties of temporal reckoning, I am not sure I would have realized what role telescoping time played in Ella's ongoing process of healing.

ELLA AND HER PARTS WERE ADAMANT THAT THEY DID NOT WANT integration, and I did not push for it. The problem for Ella was that, at the beginning, the barriers of awareness between her parts made it difficult for her to function, and crises could occur when these different parts had different beliefs, motivations and goals. For example, one of the younger parts insisted on taking a stuffed cow to class in Ella's backpack, and Ada and Violet had to struggle during lectures to keep her from pulling it out and playing with it. Another time Ella had been working hard on a final paper for a class, and then Ada came out and deleted it because she objected to the fact that it had to do with evolution. Ella, exasperated, had to start all over. My goal with Ella's parts, then, was not integration into one self but community building.

We started with strategies to increase communication among Ella's parts, such as keeping a notebook where each part could jot down things they did while they were out so others would know what to expect when they were in charge. As time went on, parts sometimes wrote e-mails to one another (and copied me). Ella and her parts eventually were able to have "team meetings" where they came together in a meeting space she created in her mind—a living room with colorful couches and pillows and toys for the younger parts.

Even so, not everything was shared among parts: strong boundaries between the thoughts, feelings and memories of different parts remained, and things did not always go smoothly. But Ella's parts gradually learned to work as a team of specialists. One was good at taking tests, one felt at ease when talking to authority figures, one was comfortable with emotional attachment, and one felt ongoing hurt but eventually began to cry softly in the background instead of taking over

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PINK, the three-year-old "part" of Ella who made this picture, used backward writing, as small children sometimes do.

Ella

and making it impossible for Ella to function. Even Violet and Ada began to team up and make lasting present-day attachments.

As Ella's college graduation approached and we came to the end of our therapy, Ella still wasn't "cured" according to the standard treatment guidelines. She was functioning well in the everyday world, although some parts (Violet, Ada, and a few others) remained present and showed no signs of going anywhere. Ella and her parts continued to insist that integration or fusion was not an option. How, then, to make sense of our work together? Was it a success or a failure?

THE ANSWER TO THIS QUESTION IS NOT BLACK-AND-WHITE. On the one hand, as Ella's parts increased their collaboration, the trajectory of her life gradually began to arc forward instead of back. She graduated from college with honors, earning a degree from one of the country's top universities. She then went on to graduate school, where she specialized in working with children with a range of special needs. She excelled in this field and told me that having her younger parts still present in the background was an enormous benefit in helping her empathize with children others found frustrating or implacable. A few years later Ella met and fell in love with a wonderful partner, with whom she shared her entire history. They eventually got married and welcomed their first child.

But life is not perfect, Ella told me recently, and she still struggles with a variety of aftereffects of the trauma she endured. She is still plagued by nightmares, though not every night. The memories of the abuse remain vivid. She still feels the presence of Violet, Ada, and a few of the others, although they rarely come out anymore. She continues to take things one step at a time as her healing journey continues.

I would like to think, then, that the therapy was a success even if Ella remains, at least partially, "symptomatic." But I emphasize that my approach with Ella might not work for everyone. Different clients can have very different needs. In Ella's case, anthropological insights helped me understand and work in collaboration with—rather than in opposition to—her inner world and envision the possibility of a healthy self that doesn't map onto the standard models.

Ella is one of those clients whose presence remains even long after the therapy has ended, and I continue to reflect on what I have learned. Ella encouraged me to share her story in the hopes that it might help others understand the realities of DID and the possibilities for finding ways forward even when the path is not well trodden. Whatever one believes about DID, Ella's story has much to teach us all about what it means to suffer unthinkable harm; to find, against all odds, a way to move on; and to be deeply, almost unbearably, human. SA

An early description of Ella's case appeared in "Inner Worlds as Social Systems: How Insights from Anthropology Can Inform Clinical Practice," by Rebecca J. Lester, in SSM—Mental Health, *Vol. 2; December 2022.*

FROM OUR ARCHIVES

The Long Shadow of Trauma. Diana Kwon; January 2022.

scientificamerican.com/magazine/sa

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Blame Game

How scientists got confident attributing disastrous weather to global warming

By Lois Parshley

Illustration by Miriam Martincic

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Lois Parshley is an investigative journalist. Her climate reporting can be found on Twitter and Mastodon @loisparshley



LAST NOVEMBER THE SPRING WEATHER IN SOUTH AMERICA JUMPED FROM COLD TO SEARING. Usually at that time of year people would have been holding backyard barbecues, or *asados,* in the lingering evening light. But on December 7 the temperature in northern Argentina, near the borders of Bolivia and Paraguay, hit 115 degrees Fahrenheit, making it one of the hottest places on Earth. The heat exacerbated a three-year drought, baking the soil and shriveling vast wheat crops before harvest.

As the Argentine government restricted wheat exports and warned people to stay indoors, a small team of scientists from around the globe logged on to Zoom. They belonged to the World Weather Attribution (WWA) group, a collaboration of climate researchers that Friederike Otto and Geert Jan van Oldenborgh formed in 2014 to address a persistent, nagging question: Is climate change making extreme weather worse and, if so, by how much? The group's ambitious goal is to provide straight answers almost as quickly as disasters strike—for the public, the media and policy makers, as well as for emergency managers and urban planners trying to understand how to prepare for the next severe event.

Just over a week after a 2021 heat dome began baking the U.S. Pacific Northwest, for example, the team released a careful and comprehensive evaluation built on previous science. It concluded that the record-breaking circumstances would have been almost impossible without human-caused climate change, noting that the temperatures "were so extreme that they lie far outside the range of historically observed temperatures." When swaths of India and Pakistan suffered heat dangerous to human life in the spring of 2022, the team estimated that climate change made the heat wave hotter and more likely. And when large parts of Pakistan flooded last summer, the group found that climate change could have increased the rainfall by as much as 50 percent.

This speed and certainty are huge advances in extreme weather analysis from a decade ago, when many scientists were reluctant to say how climate change might have contributed to individual events. The field "has completely changed," Otto told me from her office—walls covered with maps of the world—at the University of Oxford, where she is a professor of global climate science. Fredi, as colleagues call her, was born in Germany and is now a U.K. citizen. When she describes the history of attribution science, she is blunt: "At the beginning people were saying, 'You can't do this; the models aren't good enough.'" Otto adds, "We now know how to do this." Attributions in 2014 were difficult and slow, in part because it can take more than a year for a scientific study to make it through peer review. To address that lag, the WWA developed a peer-reviewed methodology to quickly conduct this kind of research and release the findings directly to the public.

A decade ago the Intergovernmental Panel on Climate Change said attribution science was not yet "fit for purpose." In contrast, a 2021 IPCC report called attribution science "robust." The growing ability to say decisively just how much climate change is to blame could have implications for everything from insurance claims and court cases to international negotiations over which nations should pay for climate adaptation. Otto also hopes the WWA's reports will show governments why it is vital to reduce emissions. And so last December, as high temperatures roasted Argentina, Bolivia and Paraguay, Otto and the rest of the WWA got to work.

RISING CONFIDENCE

ONE OF THE FIRST climate attribution studies to be widely cited by other scientists was published in 2004 in *Nature*. It came out about a year and a half after

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Europe's hottest summer in centuries, when crops failed, glaciers in the Alps shrank by as much as 10 percent and more than 30,000 people died. The lead author, Peter A. Stott, a climate scientist at the Met Office Hadley Center for Climate Science and Services in England, concluded that human influence had at least doubled the chance of the record-breaking heat wave. At the time, says Stephanie Herring, a climate scientist at the National Oceanic and Atmospheric Administration, the question was considered "super in the weeds," intriguing primarily to researchers who enjoyed debating statistical probability and the atmosphere's physical dynamics. When she began publishing an annual report on extreme events for the American Meteorological Society in 2012, "none of us expected there to be the level of public interest that this field of research ended up gaining."

Interest grew after Superstorm Sandy hit New York City and New Jersey in October 2012. Everyone wanted to know how the storm could have stayed so strong so far north. A report released months later noted that an excessive amount of Arctic sea ice had melted earlier that year, creating large regions of open water that absorbed heat from the sun, possibly contributing to Sandy's fury—although the links were still described as just one plausible theory. Scientists tend to be conservative, prone to underestimating impacts, says Kevin Trenberth, a distinguished scholar at the National Center for Atmospheric Research. Most researchers were still reluctant to discuss how climate change might have influenced a particular storm.

Advances in technology have made it easier to isolate climate's role. In the early 2000s few institutions had high-performance computing systems capable of running data-heavy climate models. Today, with cloud services, researchers can do this work at home from a laptop. It's easier to combine models and run them multiple times, increasing confidence in the results. The accuracy of models has also improved, and their resolution has become much more granular, making them better at providing more precise information about specific locations.

As the field grew, two methods developed. One, known as probabilistic event attribution, is used to estimate how much human behavior has contributed to the odds of a certain kind of event occurring, such as a heat wave. Scientists compare models of extreme weather dynamics with simulations of a world in which climate change is not happening, revealing whether factors such as increased emissions made an event more likely. The WWA's first study, for example, compared temperatures in five French cities during a 2015 heat wave with those from summers in the first half of the 1900s, revealing that climate change quadrupled the chances of the heat wave occurring.

In contrast, the conditional or "storyline" approach asks questions about specific incidents: Did climate change make the rainfall of a particular storm more intense? This method emphasizes thermodynamic

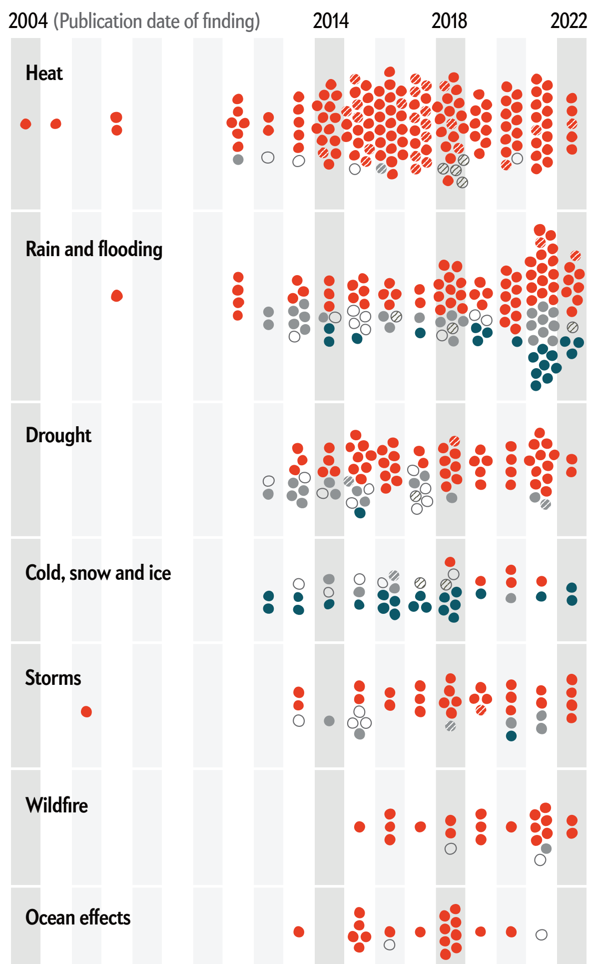
Human Actions Worsen Weather

Scientists have completed hundreds of attribution science studies since 2004. Overall, 71 percent show that climate change has made extreme weather more severe (*red dots*); it made only 9 percent of weather events less severe or less frequent (*blue dots*). Climate change worsened excessive heat 93 percent of the time, drought 69 percent of the time, and rain or flooding 56 percent of the time.

Weather events are grouped by type. Each dot represents one study; studies done very quickly—known as rapid assessments—have cross-hatched color. Date indicates the year of publication. Data for 431 studies done through May 2022 were generated by *Carbon Brief*.

Finding

- More severe or likely to occur
- No discernible difference
- Inconclusive or insufficient data
- Less severe or less likely to occur



**Events occurring fewer than 10 times in the Carbon Brief database—such as coral bleaching or river flow—have been omitted.*

Source: "Mapped: How Climate Change Affects Extreme Weather around the World," by Roz Pidcock and Robert McSweeney, in *Carbon Brief*; August 4, 2022 (data)

Graphics by Voilà:

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changes, such as warmer air holding more water vapor.

Trenberth, an early supporter of the storyline approach, says the scientific debate over the two methodologies was initially acrimonious. When a 2014 study by Martin Hoerling of NOAA, done after intense flooding in Boulder, Colo., found that climate change had not increased the chance of heavy rain in the region, Trenberth and his colleagues challenged the results. They said the study didn't consider warm sea-surface temperatures in Mexico, which Trenberth claimed added significant moisture to the atmosphere, increasing the total precipitation. Hoerling responded that Trenberth was oversimplifying. The whole debate played out in a reported news article in *Nature*.

Over time both camps realized the approaches can complement each other. "In an ideal world, you would always do both," Otto says. "They are looking at the problem in different ways." Both methods have the potential to provide important information about relative risk, says Elisabeth Lloyd, a fellow of the American Academy of Arts and Sciences. Together, the analyses could tell policy makers whether roads and bridges will have to withstand heavier rainfall and could inform emergency managers about how frequently in the future they might have to control access to those roads and bridges because of storms.

The field made further headway in 2017 after Hurricane Harvey stalled for days over the greater Houston region, dumping as much as 60 inches of rain in places, far exceeding previous records. Trenberth found that superwarm ocean water in the Gulf of Mexico created greater evaporation than normal, leading directly to excessive precipitation. A separate analysis by Otto and her colleagues indicated that climate change had added 15 percent more rainfall. Trenberth wrote that governments in regions prone to hurricanes would need to plan for greater flooding, including making upgrades to evacuation routes, building codes and power grids.

That was exactly the kind of social and political prescription that generates biting criticism that climate scientists should "stay in their lane"—do research but keep quiet about its implications. Otto says she has at times been faulted for being too political. "But there isn't such a thing as a neutral scientist," she says. "The questions we ask are always influenced by our values, by who is funding us, by where we live. Making it transparent is what makes good science—not pretending it's not happening."

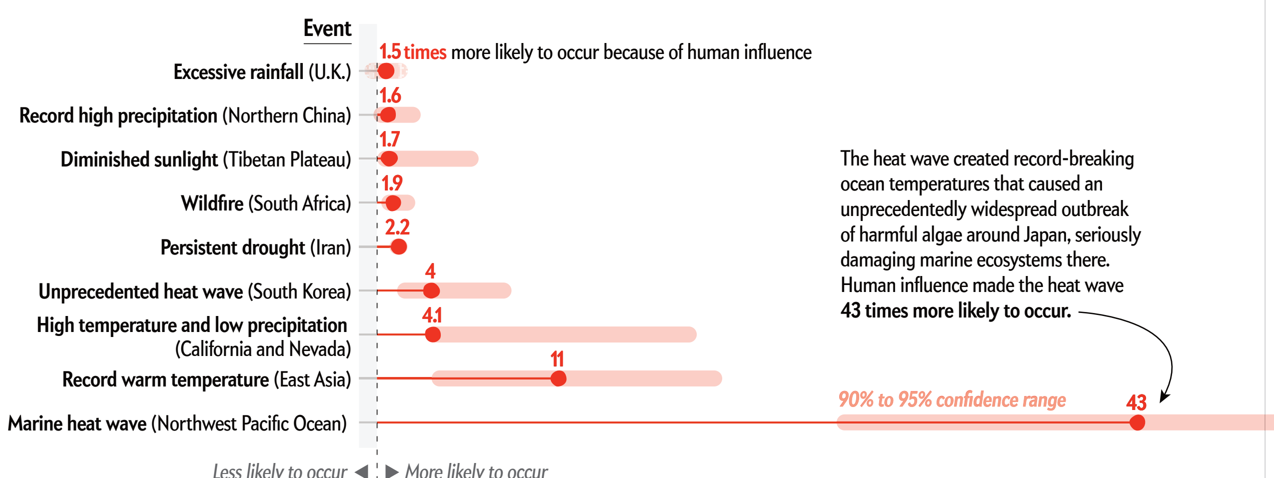
THE ARGENTINA CHALLENGE

WHEN THE WWA BEGAN, it analyzed just a few events a year. Now it meets online to discuss disasters almost every week. The small team has to prioritize which incidents it thinks merit investigation. Many of its scientists are volunteering their time, squeezing in work between research or teaching jobs and other responsibilities.

To decide which disasters to study, the scientists assess potential humanitarian impacts using criteria the WWA has developed for different kinds of events. For heat waves, factors include related deaths and whether the affected area is densely populated or particularly vulnerable. The WWA tends to take on incidents that harm many people, but it also strives to cover di-

More Heat, More Rain, Less Sun

Nine detailed case studies demonstrate the wide influence human-induced climate change can have on extreme weather, from excessive precipitation in California, to persistent drought in Iran, to diminished sunlight over the Tibetan Plateau that reduced vegetation growth. The cases, published in 2021 and 2022 in the *Bulletin of the American Meteorological Society,* specify how much more or less likely an event was to occur because of human influence.



Source: *Explaining Extreme Events of 2021 and 2022 from a Climate Perspective, Bulletin of the American Meteorological Society Special Collection, December 2022 (reference)*

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verse regions. "We don't want to do only events in the Global North because that's where we happen to work," says Sarah Kew, a climate scientist at the Royal Netherlands Meteorological Institute. Breaking new scientific ground is a factor, too, Otto says. The WWA decided not to study the Arctic blast that subjected millions of people in the U.S. to dangerously cold temperatures over the 2022 Christmas and New Year's holidays, because it had previously studied similar cold snaps in North America and didn't expect to find anything new.

The South American heat wave caught the team's attention because it met several of the WWA's criteria for heat waves: record-breaking temperatures occurring in very early summer in a vulnerable area. Although the first video conference to discuss it in late November 2022 offered some windows into the researchers' lives—Madrid's sunshine, London's gloom—the meeting began without small talk. "We have the Argentine heat wave that expanded north," said Maja Vahlberg, who works with the Red Cross Red Crescent Climate Center. "Is it La Niña–related?" Otto asked, referring to a circulation pattern in the Pacific Ocean that can make heat waves more likely in the Argentina region. In a fast-paced conversation, the team decided to reach out to scientists in South America for detailed information and quickly scheduled another meeting for early December. Twelve minutes after the call began, everyone logged off.

The WWA collaborates with local experts whenever possible, counting on them to know which data sets have the most comprehensive information about a region or how to best gather meteorological data there. At the meeting in early December, Juan Antonio Rivera, a climate scientist at the Argentine Institute of Snow Research, Glaciology and Environmental Sciences, joined the Zoom collage from his office in Mendoza. The recent drought had affected northern Argentina, southern Brazil, Uruguay and Paraguay, he told the group, but large parts of those regions lack a dense network of weather stations. One of the first tasks would be to see what data were available for analysis of how the drought intensified over time. He could help the group dig into information that might not be easy to find for people living in Europe or that might not be accessible to them because of language barriers.

The scientists on the call—some in the Netherlands wearing sweaters, others sweating in the Chilean sun—talked through options for untangling the heat wave's influence from the drought. "Every time we have a heat wave, the drought gets worse," said Anna Sörensson, a researcher at the French-Argentinean Institute for the Study of Climate and Its Impacts, who lives in Buenos Aires. Low water levels in rivers had disrupted an important agricultural export route, along with hydropower generation, she said. A transportation union had even contacted her for advice on designing new boats to work in the lower rivers.

The team had to define each event in a productive way. For every attribution study, Otto told me later, they need to find out what they can measure. For heat waves, the group looks for temperatures over a certain threshold for a given period. Droughts are more complex because they can be characterized in many ways—by lack of rain, by soil moisture or by levels of surface water. A definition may require multiple measurements. "If you have very high temperatures, you have very high evaporation, so you have low stream flow, which has huge economic impacts; you can't capture that just looking at the rainfall," Otto said.

Otto asked the team whether it could do something fast and meaningful based on just temperature and precipitation. The group bandied the options around: Heat waves are fairly straightforward to analyze because many have been studied and linked to climate change. But some WWA members advocated for a larger, slower analysis of the drought. Finally, one member asked, "Is there an option of doing both?"

Rivera impressed on the others just how striking the temperatures had been in his homeland. "November was the warmest November recorded in Argentina," he said. The group's enthusiasm swiftly built for doing a heat study quickly and giving the more complex drought research the time it required. "It's something we haven't done before—one study but published in two parts," Otto mused. Before people winked out of the video meeting and returned to their physical realities, they parceled out tasks they each would pursue offline.

Within a few weeks the scientists used five different sets of computer models to compare the characteristics of climate today with preindustrial conditions. They focused on the hottest one-week period in early December and found that climate change made the heat wave 60 times more likely to happen. Temperatures in Argentina were probably about 2.5 degrees F hotter than they otherwise would have been. Previous research suggested that amount of difference could have increased the risk of heat-related deaths by more than 5.7 percent. The WWA released its findings late in December as yet another swelter swept over Argentina. "It is noteworthy that these record temperatures occurred before the beginning of the austral summer season, making them particularly exceptional," the group wrote.

As the team turned to its drought study, power in parts of Buenos Aires failed. Wildfires broke out across northern Argentina and neighboring Chile.

"What turns any weather event into a disaster is vulnerability and exposure," Otto says. Heat records alone don't capture how people are affected. If you don't look at scientific research and disaster response together, she says, "you will just not understand what climate change means." Latin America, for example, has high levels of inequality, with marginalized communities that are more vulnerable to health consequences from extreme weather. Rivera recounted a

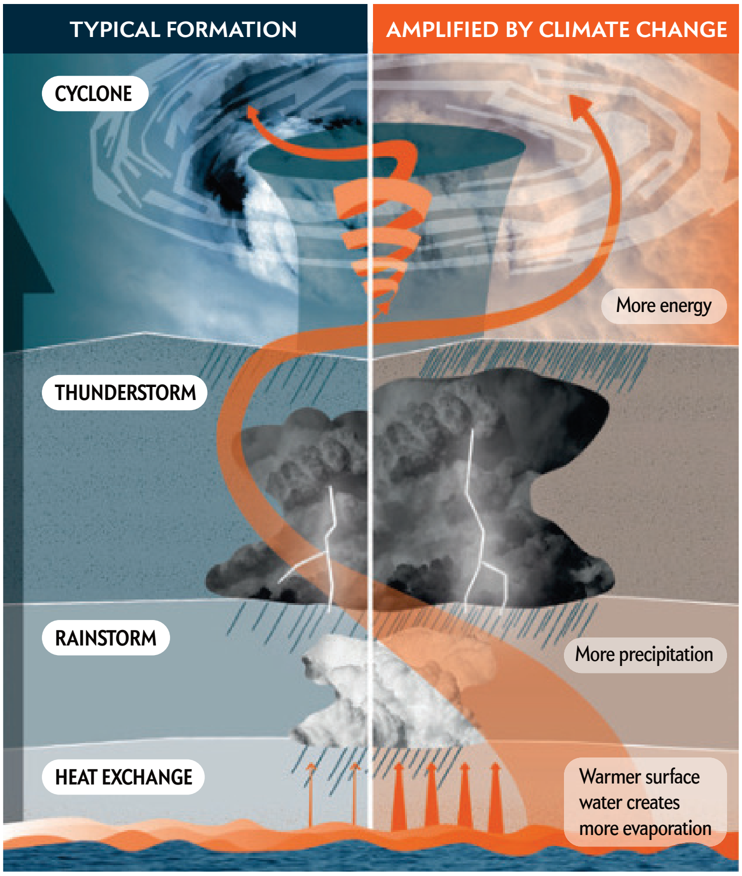
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Supercharged Cyclones

Climate change is warming the atmosphere and oceans. The extra heat can make rainstorms, snowstorms, thunderstorms and hurricanes stronger, resulting in more deaths and damage. Attribution science can determine how much climate change has intensified a given storm.

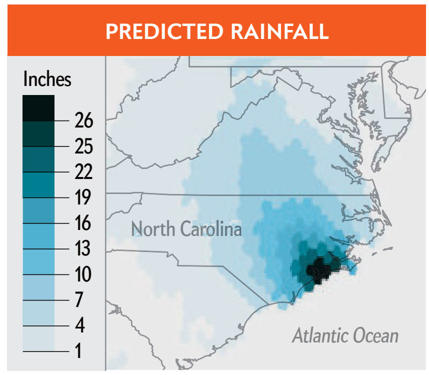
How Climate Change Strengthens Hurricanes

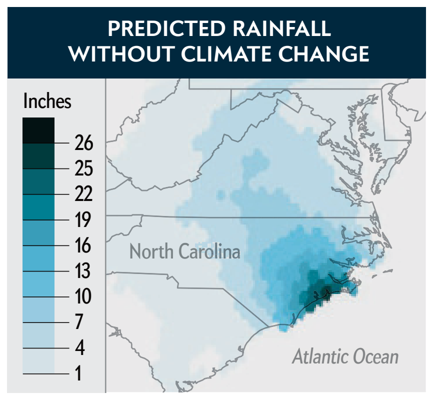
A warm ocean creates extensive evaporation. As abundant vapor rises, it condenses, producing heavy rain, which releases heat, drawing up air that can develop into strong updrafts and thunderstorms. If an atmospheric disturbance sweeps through, the storm system can begin to circulate, forming a hurricane (synonymous with cyclone). By heating water and air further, climate change can create even more evaporation, more precipitation and more energy in a rotating system, supercharging a hurricane.



Extra Rain from Hurricane Florence

Attribution science can forecast how much more rain a hurricane will drop, almost in real time. Kevin Reed and Michael Wehner predicted precipitation for Hurricane Florence as it hit North Carolina in September 2018. They calculated that the hurricane would produce 5 percent more rain (*top*) than what would have fallen without climate change's effects (*bottom*). Their prediction closely matched the extremes Florence ultimately delivered.





Kevin Reed/Stony Brook University and Michael Wehner/Lawrence Berkeley National Laboratory (*rainfall maps*)

meeting where desperate farmers knelt on the dry soil and prayed for rain.

Although Argentina's plight largely failed to make headlines north of the equator, its impact will be felt globally. The country is a major wheat exporter; a trade group estimates half of the wheat crop will be lost in 2023 because of the drought, and all crop losses could amount to $10 billion. Analysts warned that the country's agricultural failures would further increase food prices around the world.

The WWA stands out in the climate research sphere for its willingness to directly address social factors. Otto points to a 2022 study that the WWA conducted in Africa's Sahel region, which she says had basically nothing to do with the weather. The region's economy relies on rain to irrigate crops and sustain herds, but in 2021 a delayed rainy season caused cascading food insecurity. "Even small shifts in rainfall," the WWA wrote, "impact the already limited food supply." Because of large uncertainties in data sets, the team could not determine whether there was a climate signal in the rainfall shifts, but it warned that the region is "vulnerable to future impacts of climate change on global breadbaskets."

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LIFE AND DEATH

EVEN AS ATTRIBUTION SCIENCE improves, some experts argue that climate scientists are still underselling their conclusions—an important factor as the field begins to move out of academic circles and into public proceedings such as court cases. A related issue is that evidence introduced in court often lags the latest science. In a 2021 *Nature Climate Change* study, Otto and her collaborators examined 73 climate lawsuits worldwide and found that the evidence entered was 10 years out of date. "I think it just takes some time for new science to filter through into politics," Otto says, adding, "it should be faster."

The WWA's work has influenced at least one ruling. Its study of the 2019–2020 bushfires in Australia concluded that climate change played a part in increasing the overall seasonal fire risk by a factor of nine. In 2021 an Australian court considered this result when it found that the New South Wales Environment Protection Agency had failed to protect the environment, requiring the state to reduce greenhouse gas emissions.

As extreme weather becomes more common, keeping up becomes harder. This past winter more than 20 people died as a series of powerful atmospheric river storms dumped heavy rain and snow over California. The WWA decided to not study the deluges, in part because demand for attribution work is far outpacing capacity. "It's a small community, and funding is limited," says Michael Wehner, a climate scientist at Lawrence Berkeley National Laboratory.

Like the WWA, Wehner and his collaborator, Kevin Reed of Stony Brook University, are trying to conduct attribution studies in almost real time. They analyzed Hurricane Ian in September 2022 while the storm was still clobbering Florida. Their quick work was possible partly because they had just published a paper on the 2020 hurricane season, finding that climate change caused it to be 5 percent wetter. They added Ian's conditions to their previous models. "We probably could have done it faster, but Kevin went out to dinner," Wehner jokes. They decided to issue a timely statement prior to the lengthy peer-review process, declaring it likely that climate change had added 10 percent to Ian's rainfall.

Wehner often has to turn down requests, which prompted him to publish a 2022 paper in *PLOS Climate* arguing that many attribution studies can now be considered routine and should move out of academia. The science has matured. "It could be operationalized," Wehner says, "like a weather forecast." Otto would welcome the change. "I really want this to be taken over by NOAA," she says, "or by Copernicus," the European Union's Earth observation program. "Not only would it enable the [scientific] community to do much more, it would have a much more direct route into national policies."

In the U.S., NOAA recently began a pilot project led by David Easterling, director of national climate assessment there, to develop this kind of capability. NOAA has some clear advantages: it gets real-time feeds from weather stations across the country and has access to climate model development at the Geophysical Fluid Dynamics Laboratory at Princeton University. Easterling hopes that, given the agency's reputation for being unbiased, if "NOAA starts saying, 'This event is made 15 percent worse due to climate change,' that's going to begin to change a lot of attitudes" among people who may still be skeptical about climate change.

As attribution science continues to grow, it could play an important role in helping society prepare for greater risks, including informing building codes and highlighting the need for drastic emissions reductions, says Susanne Moser, a social scientist and consultant who specializes in climate adaptation. Professional engineering associations are already moving toward adaptive designs such as seawalls built with broader bases so they can be made taller as oceans rise. She points to California and other forward-looking states that are studying how to incorporate climate information into their infrastructure plans, work that will be valuable in rebuilding after that state's recent floods.

> "I really want [attribution science] to be taken over by NOAA or by Copernicus. It would have a much more direct route into national policies." *—Friederike Otto*

Some countries will have an easier time than others financing such sweeping adaptations, which is why the 2022 United Nations Climate Change Conference (or COP27) created a "loss and damage" fund to help low-income countries, whose greenhouse gas emissions have been relatively small. But there is still no definition of what counts as climate-inflicted damage, Otto says. "What evidence would you need? Who provides that?" She says further attribution work will be required to determine international liability or compensation amounts.

During a recent video call with me, Otto said the work had grown increasingly stressful. "In the beginning, it wasn't so much in the public limelight—it didn't feel like quite so much pressure," she said. In 2021 *Time* included her in its annual list of the world's 100 most influential people. Now she gets recognized when she's out shopping or at her dance studio.

Applying attribution science might not be so daunting if the discipline had begun to grow up decades ago, when climate change was already a known issue, Otto says. But today her work is a race against time. "People are suffering," she says, "and are unable to deal with the consequences." SA

FROM OUR ARCHIVES

Vapor Storms. Jennifer A. Francis; November 2021.

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PHYSICS

Mimicking Matter with Light

Experiments that imitate materials with light waves reveal the quantum basis of exotic physical effects

By Charles D. Brown II

Photographs by Spencer Lowell

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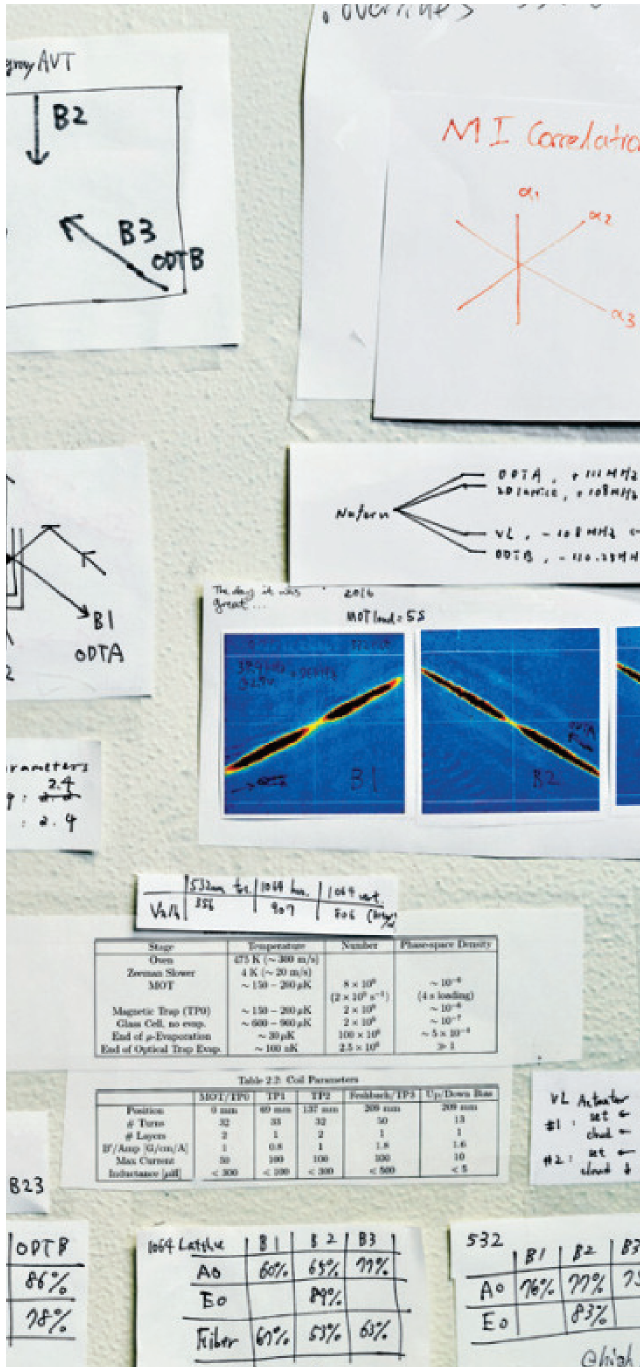


INSIDE A HEXAGON-SHAPED ultrahigh vacuum chamber, physicists use laser optics to create optical lattices that mimic the crystal lattices in solid materials.

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Charles D. Brown II is an assistant professor of physics at Yale University, where he uses optical lattices to study the condensed matter physics of quasicrystals.



MANY SEEMINGLY MUNDANE MATERIALS, such as the stainless steel on refrigerators or the quartz in a countertop, harbor fascinating physics inside them. These materials are crystals, which in physics means they are made of highly ordered repeating patterns of regularly spaced atoms called atomic lattices. How electrons move through a lattice, hopping from atom to atom, determines many of a solid's properties, such as its color, transparency, and ability to conduct heat and electricity. For example, metals are shiny because they contain lots of free electrons that can absorb light and then reemit most of it, making their surfaces gleam.

In certain crystals the behavior of electrons can create properties that are much more exotic. The way electrons move inside graphene—a crystal made of carbon atoms arranged in a hexagonal lattice—produces an extreme version of a quantum effect called tunneling, whereby particles can plow through energy barriers that classical physics says should block them. Graphene also exhibits a phenomenon called the quantum Hall effect: the amount of electricity it conducts increases in specific steps whose size depends on two fundamental constants of the universe. These kinds of properties make graphene intrinsically interesting as well as potentially useful in applications ranging from better electronics and energy storage to improved biomedical devices.

I and other physicists would like to understand what's going on inside graphene on an atomic level, but it's difficult to observe action at this scale with current technology. Electrons move too fast for us to capture the details we want to see. We've found a clever way to get around this limitation, however, by making matter out of light. In place of the atomic lattice, we use light waves to create what we call an optical lattice. Our optical lattice has the exact same geometry as the atomic lattice. In a recent experiment, for instance, my team and I made an optical version of gra-

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phene with the same honeycomb lattice structure as the standard carbon one. In our system, we make cold atoms hop around a lattice of bright and dim light just as electrons hop around the carbon atoms in graphene.

With cold atoms in an optical lattice, we can magnify the system and slow down the hopping process enough to actually see the particles jumping around and make measurements of the process. Our system is not a perfect emulation of graphene, but for understanding the phenomena we're interested in, it's just as good. We can even study lattice physics in ways that are impossible in solid-state crystals. Our experiments revealed special properties of our synthetic material that are directly related to the bizarre physics manifesting in graphene.

TOPOLOGICAL MATERIALS

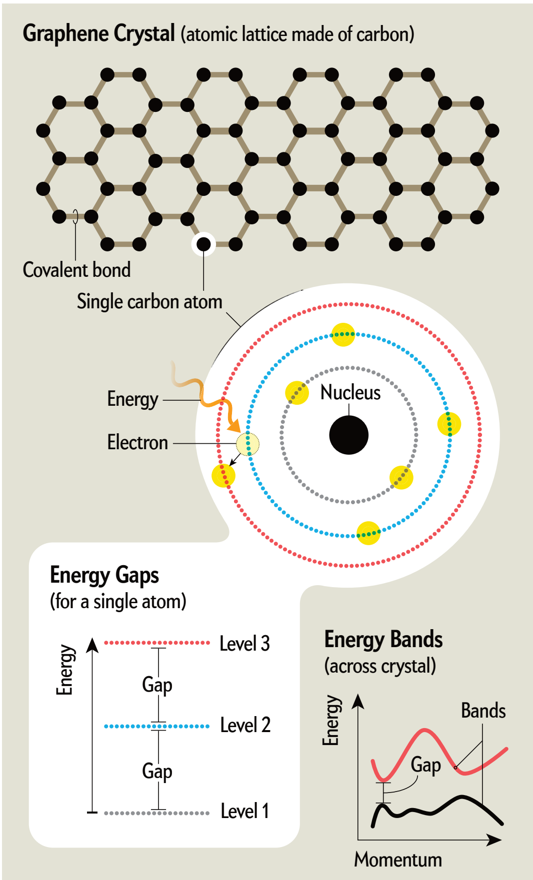
THE CRYSTAL PHENOMENA we investigate result from the way quantum mechanics limits the motion of wavelike particles. After all, although electrons in a crystal have mass, they are both particles and waves (the same is true for our ultracold atoms). In a solid crystal these limits restrict a single electron on a single atom to only one value of energy for each possible movement pattern (called a quantum state). All other amounts of

CHARLES D. BROWN II (*above*) uses optical lattices to probe exotic physics. Notes on a wall (*left*) offer reminders for alignment of optical lattice laser beams and other methods.

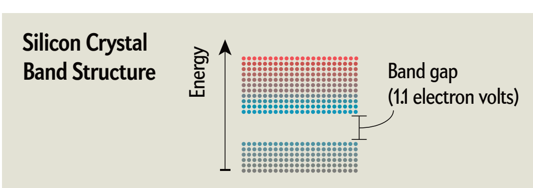
Photograph by Wayne Lawrence (right)

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energy are forbidden. Different states have separate and distinct—discrete—energy values. But a chunk of solid crystal the size of a grape typically contains more atoms (around 10^{23}) than there are grains of sand on Earth. The interactions between these atoms and electrons cause the allowed discrete energy values to spread out and smear into allowed *ranges* of energy called bands. Visualizing a material's energy band structure can immediately reveal something about that material's properties.



For instance, a plot of the band structure of silicon crystal, a common material used to make rooftop solar cells, shows a forbidden energy range—also known as a band gap—that is 1.1 electron volts wide. If electrons can jump from states with energies below this gap to states with energies above the gap, they can flow through the crystal. Fortunately for humanity, the band gap of this abundant material overlaps well with the wavelengths present in sunlight. As silicon crystal absorbs sunlight, electrons begin to flow through it—allowing solar panels to convert light into usable electricity.

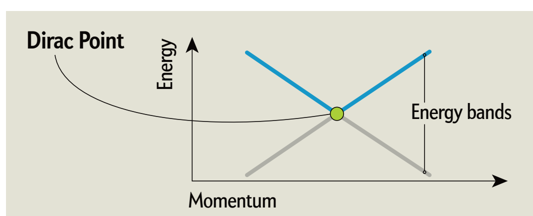


The band structure of certain crystals defines a class of materials known as topological. In mathematics, topology describes how shapes can be transformed without being fundamentally altered. "Transformation" in this context means to deform a shape—to bend or stretch it—without creating or destroying any kind of hole. Topology thus distinguishes baseballs, sesame bagels and shirt buttons based purely on the number of holes in each object.

Topological materials have topological properties hidden in their band structure that similarly allow some kind of transformation while preserving something essential. These topological properties can lead to measurable effects. For instance, some topological materials allow electrons to flow only around their edges and not through their interior. No matter how you deform the material, the current will still flow only along its surface.

I have become particularly interested in certain kinds of topological material: those that are two-dimensional. It may sound odd that 2-D materials exist in our 3-D world. Even a single sheet of standard printer paper, roughly 0.004 inch thick, isn't truly 2-D—its thinnest dimension is still nearly one million atoms thick. Now imagine shaving off most of those atoms until only a single layer of them remains; this layer is a 2-D material. In a 2-D crystal, the atoms and electrons are confined to this plane because moving off it would mean exiting the material entirely.

Graphene is an example of a 2-D topological material. To me, the most intriguing thing about graphene is that its band structure contains special spots known as Dirac points. These are positions where two energy bands take on the same value, meaning that at these points electrons can easily jump from one energy band to another. One way to understand Dirac points is to study a plot of the energy of different bands versus an electron's momentum—a property associated with the particle's kinetic energy. Such plots show how an electron's energy changes with its movement, giving us a direct probe into the physics we're interested in. In these plots, a Dirac point looks like a place where two energy bands touch; at this point they're equal, but away from this point the gap between the bands grows linearly. Graphene's Dirac points and the associated topology are connected to this material's ability to display a form of the quantum Hall effect that's unique even among 2-D materials—the half-integer quantum Hall effect—and the special kind of tunneling possible within it.



ARTIFICIAL CRYSTALS

TO UNDERSTAND what's happening to electrons at Dirac points, we need to observe them up close. Our optical lattice experiments are the perfect way to do this. They offer a highly controllable replica of the material that

Graphics by Jen Christiansen
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GRADUATE STUDENTS at the University of California, Berkeley, review optical lattice experiment data.

we can uniquely manipulate in a laboratory. As substitutes for the electrons, we use ultracold rubidium atoms chilled to temperatures roughly 10 million times colder than outer space. And to simulate the graphene lattice, we turn to light.

Light is both a particle and a wave, which means light waves can interfere with one another, either amplifying or canceling other waves depending on how they are aligned. We use the interference of laser light to make patterns of bright and dark spots, which become the lattice. Just as electrons in real graphene are attracted to certain positively charged areas of a carbon hexagon, we can arrange our optical lattices so ultracold atoms are attracted to or repelled from analogous spots in them, depending on the wavelength of the laser light that we use. Light with just the right energy (resonant light) landing on an atom can change the state and energy of an electron within it, imparting forces on the atom. We typically use "red-detuned" optical lattices, which means the laser light in the lattice has a wavelength that's longer than the wavelength of the resonant light. The result is that the rubidium atoms feel an attraction to the bright spots arranged in a hexagonal pattern.

We now have the basic ingredients for an artificial crystal. Scientists first imagined these ultracold atoms in optical lattices in the late 1990s and constructed them in the early 2000s. The spacing between the lattice points of these artificial crystals is hundreds of nanometers rather than the fractions of a nanometer that separate atoms in a solid crystal. This larger distance means that artificial crystals are effectively magnified versions of real ones, and the hopping process of atoms within them is much slower, allowing us to directly image the movements of the ultracold atoms. In addition, we can manipulate these atoms in ways that aren't possible with electrons.

I was a postdoctoral researcher in the Ultracold Atomic Physics group at the University of California, Berkeley, from 2019 to 2022. The lab there has two special tables (roughly one meter wide by two and a half meters long by 0.3 meter high), each weighing roughly one metric ton and floating on pneumatic legs that dampen vibrations. Atop each table lie hundreds of optical components: mirrors, lenses, light detectors, and more. One table is responsible for producing laser light for trapping, cooling and imaging rubidium atoms. The other table holds an "ultrahigh" vacuum chamber made of steel with a vacuum pressure less than that of low-Earth orbit, along with hundreds more optical components.

The vacuum chamber has multiple, sequential compartments with different jobs. In the first compartment, we heat a five-gram chunk of rubidium metal to more than 100 degrees Celsius, which causes it to emit a vapor of rubidium atoms. The vapor gets blasted into the next compartment like water spraying from a hose. In the second compartment, we use magnetic fields and laser light to slow the vapor down. The sluggish vapor then flows into another compartment: a magneto-optical trap, where it is

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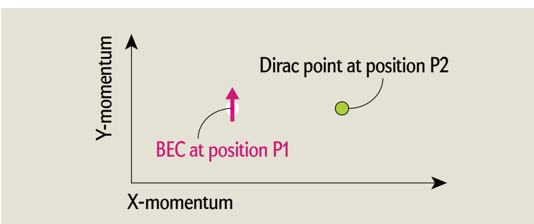
captured by an arrangement of magnetic fields and laser light. Infrared cameras monitor the trapped atoms, which appear on our viewing screen as a bright glowing ball. At this point the atoms are colder than liquid helium.

We then move the cold cloud of rubidium atoms into the final chamber, made entirely of quartz. There we shine both laser light and microwaves on the cloud, which makes the warmest atoms evaporate away. This step causes the rubidium to transition from a normal gas to an exotic phase of matter called a Bose-Einstein condensate (BEC). In a BEC, quantum mechanics allows atoms to delocalize—to spread out and overlap with one another so that all the atoms in the condensate act in unison. The temperature of the atoms in the BEC is less than 100 nanokelvins, one billion times colder than liquid nitrogen.

At this point we shine three laser beams separated by 120 degrees into the quartz cell (their shape roughly forms the letter Y). At the intersection of the three beams, the lasers interfere with one another and produce a 2-D optical lattice that looks like a honeycomb pattern of bright and dark spots. We then move the optical lattice so it overlaps with the BEC. The lattice has plenty of space for atoms to hop around, even though it extends over a region only as wide as a human hair. Finally, we collect and analyze pictures of the atoms after the BEC has spent some time in the optical lattice. As complex as it is, we go through this entire process once every 40 seconds or so. Even after years of working on this experiment, when I see it play out, I think to myself, "Wow, this is incredible!"

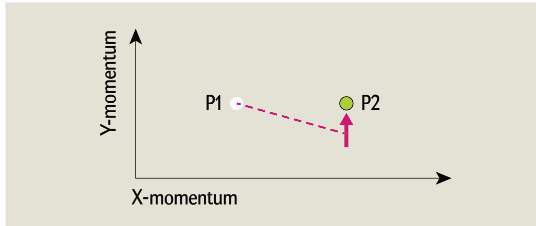
THE SINGULARITY

LIKE REAL GRAPHENE, our artificial crystal has Dirac points in its band structure. To understand why these points are significant topologically, let's go back to our graph of energy versus momentum, but this time let's view it from above so we see momentum plotted in two directions—right and left, and up and down. Imagine that the quantum state of the BEC in the optical lattice is represented by an upward arrow at position one (P1) and that a short, straight path separates P1 from a Dirac point at position two (P2).

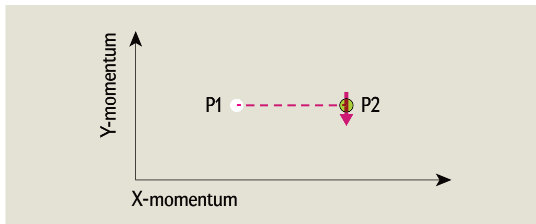


To move our BEC on this graph toward the Dirac point, we need to change its momentum—in other words, we must actually move it in physical space. To put the BEC at the Dirac point, we need to give it the precise momentum values corresponding to that point on the plot. It turns out that it's easier, experimentally, to shift the optical lattice—to change *its* momentum—and leave the BEC as is; this movement gives us the same end result. From an atom's point of view, a stationary BEC in a moving lattice is the same as a moving BEC in a stationary lattice. So we adjust the position of the lattice, effectively giving our BEC a new momentum and moving it over on our plot.

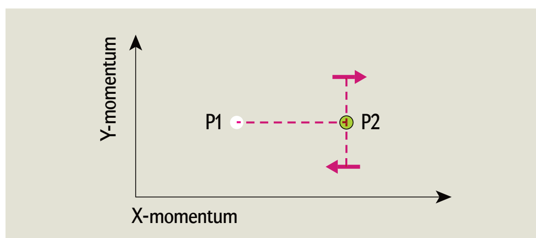
If we adjust the BEC's momentum so that the arrow representing it moves slowly on a straight path from P1 toward P2 but just misses P2 (meaning the BEC has slightly different momentum than it needs to reach P2), nothing happens—its quantum state is unchanged. If we start over and move the arrow even more slowly from P1 toward P2 on a path whose end is even closer to—but still does not touch—P2, the state again is unchanged.



Now imagine that we move the arrow from P1 directly through P2—that is, we change the BEC's momentum so that it's exactly equal to the value at the Dirac point: we will see the arrow flip completely upside down. This change means the BEC's quantum state has jumped from its ground state to its first excited state.



What if instead we move the arrow from P1 to P2, but when it reaches P2, we force it to make a sharp left or right turn—meaning that when the BEC reaches the Dirac point, we stop giving it momentum in its initial direction and start giving it momentum in a direction perpendicular to the first one? In this case, something special happens. Instead of jumping to an excited state as if it had passed straight through the Dirac point and instead of going back down to the ground state as it would if we had turned it fully around, the BEC ends up in a superposition when it exits the Dirac point at a right angle. This is a purely quantum phenomenon in which the BEC enters a state that is both excited and not. To show the superposition, our arrow in the plot rotates 90 degrees.



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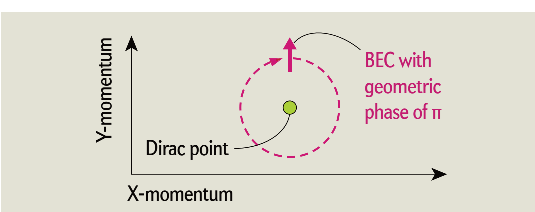
Our experiment was the first to move a BEC through a Dirac point and then turn it at different angles. These fascinating outcomes show that these points, which had already seemed special based on graphene's band structure, are truly exceptional. And the fact that the outcome for the BEC depends not just on whether it passes through a Dirac point but on the direction of that movement shows that at the point itself, the BEC's quantum state can't be defined. This shows that the Dirac point is a singularity—a place where physics is uncertain.

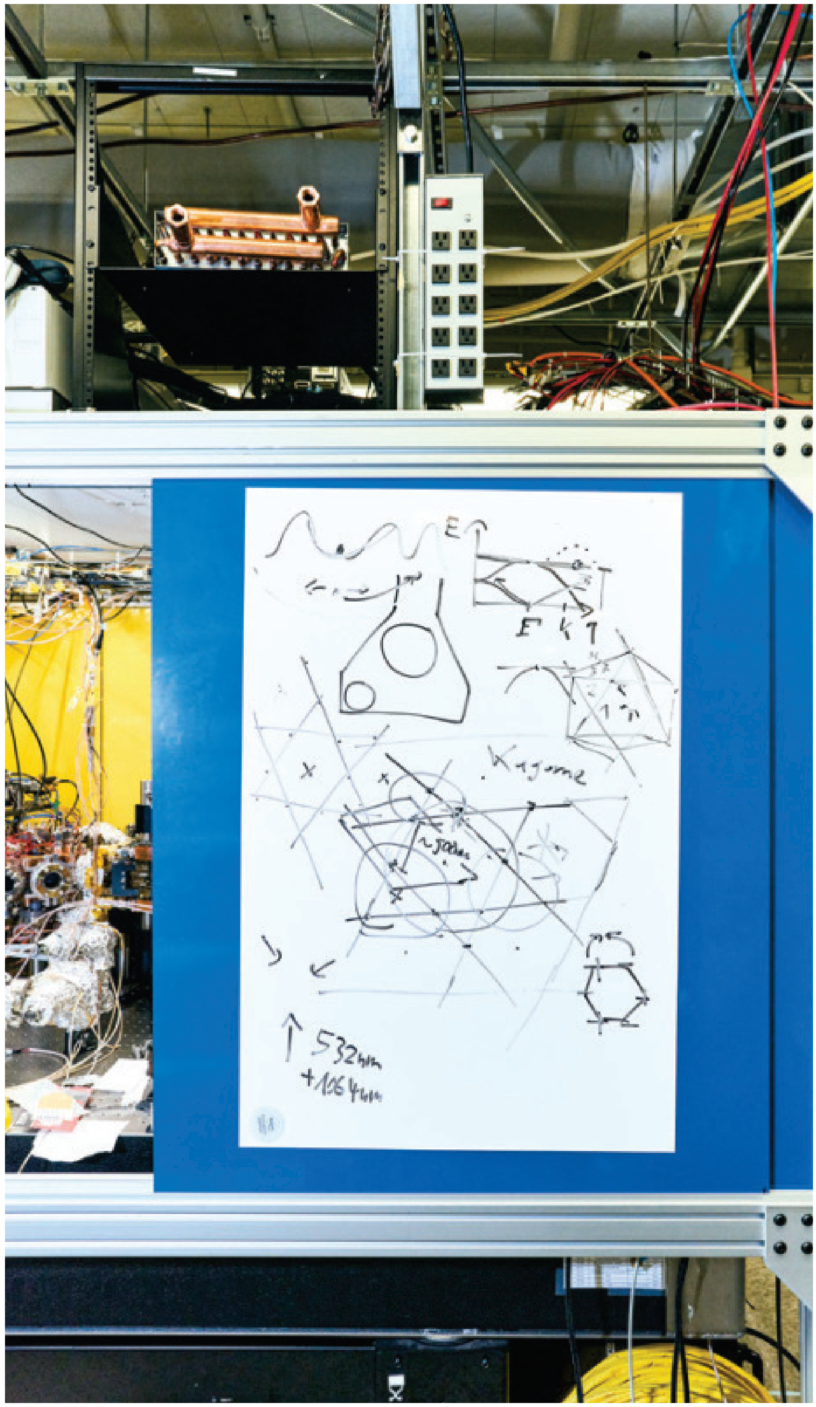
We also measured another interesting pattern. If we moved the BEC faster as it traveled near, but not through, the Dirac point, the point would cause a rotation of the BEC's quantum state that made the point seem larger. In other words, it encompassed a broader range of possible momentum values than just the one precise value at the point. The more slowly we moved the BEC, the smaller the Dirac point seemed. This behavior is uniquely quantum mechanical in nature. Quantum physics is a trip!

Although I just described our experiment in a few paragraphs, it took six months of work to get results. We spent lots of time developing new experimental capabilities that had never been used before. We were often unsure whether our experiment would work. We faced broken lasers, an accidental 10-degree-C temperature spike in the lab that misaligned all the optical components (there went three weeks), and disaster when the air in our building caused the lab's temperature to fluctuate, preventing us from creating a BEC. A great deal of persistent effort carried us through and eventually led to our measuring a phenomenon even more exciting than a Dirac point: another kind of singularity.

GEOMETRIC SURPRISES

BEFORE WE EMBARKED on our experiment, a related project with artificial crystals in Germany showed what happens when a BEC moves in a circular path around a Dirac point. This team manipulated the BEC's momentum so that it took on values that would plot a circle in the chart of left-momentum versus up-down momentum. While going through these transformations, the BEC never touched the Dirac point. Nevertheless, moving around the point in this pattern caused the BEC to acquire something called a geometric phase—a term in the mathematical description of its quantum phase that determines how it evolves. Although there is no physical interpretation of a geometric phase, it's a very unusual property that appears in quantum mechanics. Not every quantum state has a geometric phase, so the fact that the BEC had one here is special. What's even more special is that the phase was exactly π.



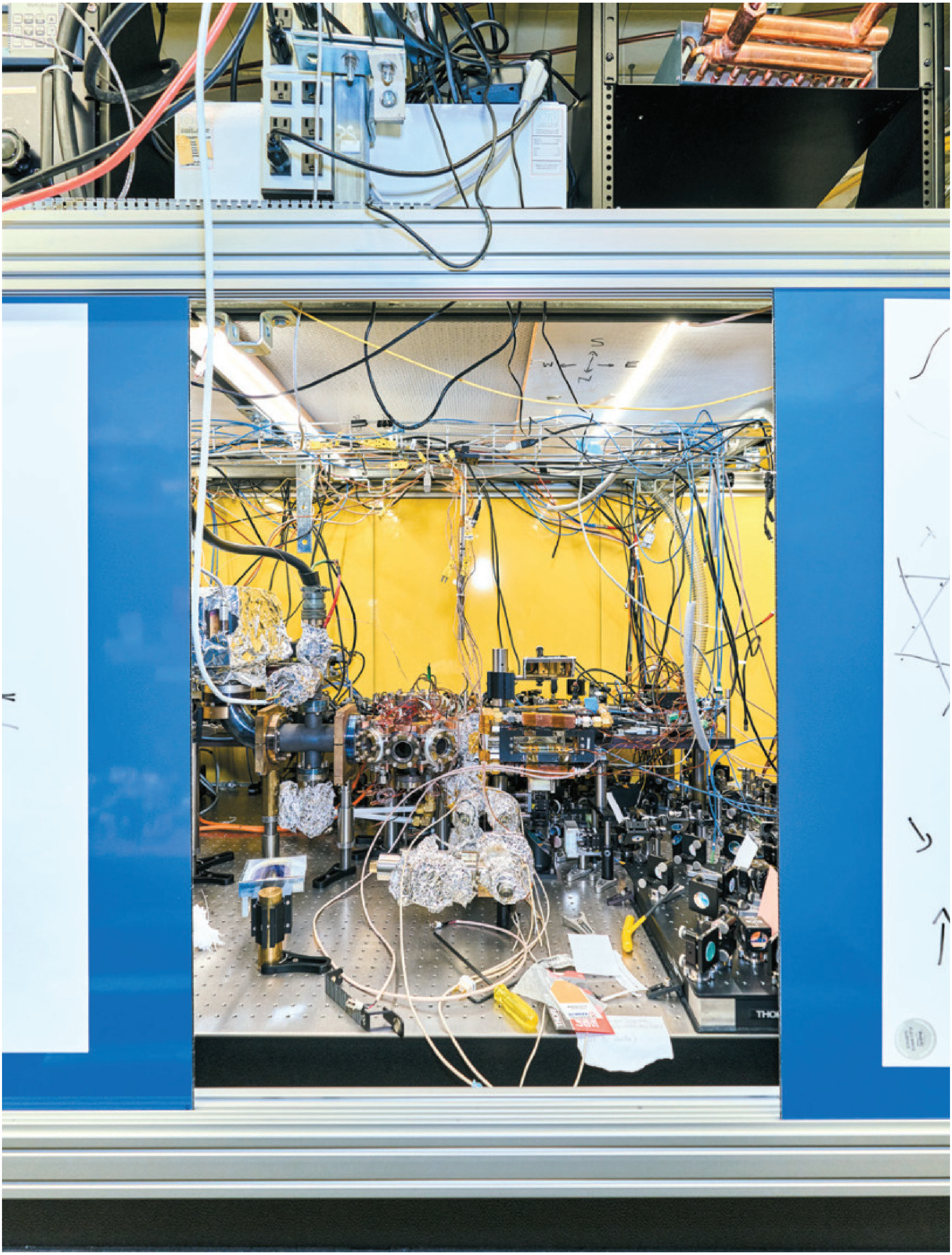


AN ILLUSTRATION helps scientists visualize complex ideas.

My team decided to try a different technique to confirm the German group's measurement. By measuring the rotation of the BEC's quantum state as we turned it away from the Dirac point at different angles, we reproduced the earlier findings. We discovered that the BEC's quantum state "wraps" around the Dirac point exactly once. Another way to say this is that as you move a BEC through momentum space all the way around a Dirac point, it goes from having all its particles in the ground state to having all its particles in the first excited state, and then they all return to the ground state. This measurement agreed with the German study's results.

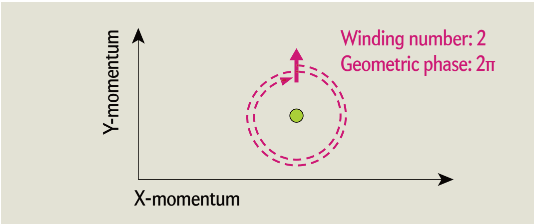
This wrapping, independent of a particular path or

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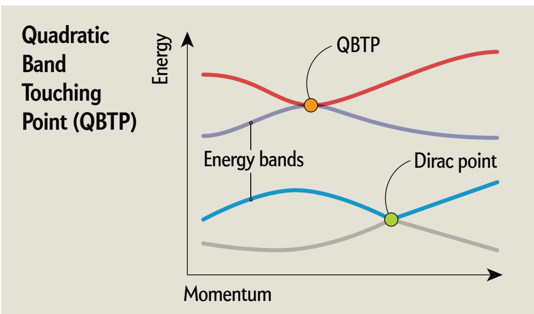


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the speed the path is traveled, is a topological property associated with a Dirac point and shows us directly that this point is a singularity with a so-called topological winding number of 1. In other words, the winding number tells us that after a BEC's momentum makes a full circle, it comes back to the state it started in. This winding number also reveals that every time it goes around the Dirac point, its geometric phase increases by π.

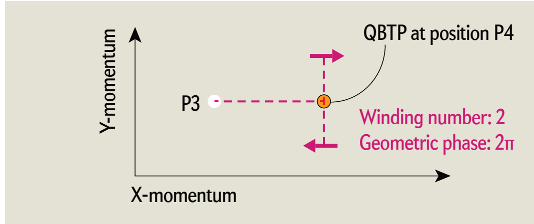


Furthermore, we discovered that our artificial crystal has another kind of singularity called a quadratic band touching point (QBTP). This is another point where two energy bands touch, making it easy for electrons to jump from one to another, but in this case it's a connection between the second excited state and the third (rather than the ground state and the first excited state as in a Dirac point). And whereas the gap between energy bands near a Dirac point grows linearly, in a QBTP it grows quadratically.



In real graphene, the interactions between electrons make QBTPs difficult to study. In our system, however, QBTPs became accessible with just one weird trick.

Well, it's not really so weird, nor is it technically a trick, but we did figure out a specific technique to investigate a QBTP. It turns out that if we give the BEC a kick and get it moving before we load it into the optical lattice, we can access a QBTP and study it with the same method we used to investigate the Dirac point. Here, in the plot of momentum space, we can imagine new points P3 and P4, where P3 is an arbitrary starting point in the second excited band and a QBTP lies at P4. Our measurements showed that if we move the BEC from P3 directly through P4 and turn it at various angles, just as we did with the Dirac point, the BEC's quantum state wraps exactly twice around the QBTP. This result means the BEC's quantum state picked up a geometric phase of exactly 2π. Correspondingly, instead of a topological winding number of 1, like a Dirac point has, we found that a QBTP has a topological winding number of 2, meaning that the state must rotate in momentum space around the point exactly twice before it returns to the quantum state it started in.



This measurement was hard-won. We tried nearly daily for an entire month before it eventually worked—we kept finding fluctuations in our experiment whose sources were hard to pinpoint. After much effort and clever thinking, we finally saw the first measurement in which a BEC's quantum state exhibited wrapping around a QBTP. At that moment I thought, "Oh, my goodness, I *might* actually land a job as a professor." More seriously, I was excited that our measurement technique showed itself to be uniquely suited to reveal this property of a QBTP singularity.

These singularities, with their strange geometric phases and winding numbers, may sound esoteric. But they are directly related to the tangible properties of the materials we study—in this case the special abilities of graphene and its promising future applications. All these changes that occur in the material's quantum state when it moves through or around these points manifest in cool and unusual phenomena in the real world.

Scientists have predicted, for instance, that QBTPs in solid materials are associated with a type of exotic high-temperature superconductivity, as well as anomalous properties that alter the quantum Hall effect and even electric currents in materials whose flow is typically protected, via topology, from disruption. Before attempting to further investigate this exciting physics, we want to learn more about how interactions between atoms in our artificial crystal change what we observe in our lab measurements.

In real crystals, the electrons interact with one another, and this interaction is usually quite important for the most striking physical effects. Because our experiment was the first of its kind, we took care to ensure that our atoms interacted only minimally to keep things simple. An exciting question we can now pose is: Could interactions cause a QBTP singularity to break apart into multiple Dirac points? Theory suggests this outcome may be possible. We look forward to cranking up the interatomic interaction strength in the lab and seeing what happens. SA

THE ULTRA-HIGH VACUUM CHAMBER is surrounded by a maze of cables, optics and delicate instruments.

FROM OUR ARCHIVES

The Bose-Einstein Condensate. Eric A. Cornell and Carl E. Wieman; March 1998.

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Whispers

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LINGUISTICS

An endangered language family suggests that early humans used their bodies as a model for reality

By Anvita Abbi

Illustration by Islenia Milien

from Deep Time

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Anvita Abbi is a linguist specializing in Indigenous languages. She received the Padma Shri Award in 2013 from the president of India and the Kenneth L. Hale Award in 2015 from the Linguistic Society of America. Abbi serves on the expert committee of the UNESCO World Atlas of Languages.



ONE MORNING IN DECEMBER 2004, ELDERS AND CHILDREN WERE WANDERING ON the shore of Strait Island in the Bay of Bengal when one of them noticed something odd. The sea level was low, and weird-looking creatures that normally inhabit the deep twilight zone of the ocean were bobbing near the water's surface. "*Sare ukkuburuko!*"—the sea has turned upside down!—shouted Nao Junior. One of the last inheritors of wisdom transmitted over thousands of generations through his mother tongue, he knew what this bizarre phenomenon signified. So did other Indigenous peoples of the Andaman Islands. They all raced inland and uphill, their ancestral knowledge saving them from the devastating tsunami that slammed onto coastlines across the Indian Ocean minutes later and swept away some 225,000 people.

When I first met Nao Jr., at the turn of the millennium, he was in his 40s and one of only nine members of his Indigenous group, Great Andamanese, who still spoke the idiom of his ancestors; the youngsters preferred Hindi. As a linguist with a passion for decoding structure, I had researched more than 80 Indian languages from five different families: Indo-European (to which Hindi belongs), Dravidian, Austroasiatic, Tibeto-Burman and Tai-Kadai. I was on the islands to document their Indigenous voices before they faded into whispers. What little I heard was so baffling that I returned many times in later years to try to pin down the principles undergirding Great Andamanese languages.

What my main teachers, Nao Jr. and a woman named Licho, spoke was a pastiche of languages that had had some 5,000 speakers in the mid-19th century. The modern vocabulary was highly variable, derived from several languages that were originally spoken on North Andaman. What was truly alien to me, however, was the grammar—it was unlike anything I had ever encountered.

A language embodies a worldview and, like a civilization, changes and grows in layers. Words or phrases that are frequently used morph into ever more abstract and compressed grammatical forms. For instance, the suffix "-ed," signifying the past tense in modern English, originated in "did" (that is, "did use" became "used"); Old English's *in steed* and *on gemong* became "instead" and "among," respectively. These kinds of transitions make historical linguistics rather like archaeology. Just as an archaeologist carefully excavates a mound to reveal different epochs of a city-state stacked on one another, so can a linguist separate the layers of a language to uncover the stages of its evolution. It would take years of Nao Jr. and Licho patiently enduring my interrogations and fumbles for me to finally learn their language's foundational rule.

Great Andamanese, it turns out, is exceptional among the world's languages in its anthropocentrism. It uses categories derived from the human body to describe abstract concepts such as spatial orientation and relations between objects. To be sure, in English we might say things like "the room faces the bay," "the chair leg broke" and "she heads the firm." But in Great Andamanese such descriptions take an extreme form, with morphemes, or meaningful sound segments, that designate different zones of the body getting attached to nouns, verbs, adjectives and adverbs—indeed, to every part of speech—to make diverse meanings. Because no other known language has a grammar based on the human body or shares cognates—words that are similar in meaning and pronunciation, indicating a genealogical connection—with Great Andamanese, the language constitutes its own family.

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The most enduring aspect of a language is its structure, which can persist over millennia. My studies indicate that the Great Andamanese were effectively isolated for thousands of years, during which time their languages evolved without discernible influence from other cultures. Genetic research corroborates this view, showing that these Indigenous people descend from one of the first groups of modern humans to migrate out of Africa. Following the coastline of the Indian subcontinent, they reached the Andaman archipelago perhaps 50,000 years ago and have lived there in virtual isolation ever since. The core principles of their languages reveal that these early humans conceptualized the world through their bodies.

PIECES OF THE PUZZLE

WHEN I ARRIVED in 2001 in Port Blair, the region's main town, to conduct a preliminary survey of Indigenous languages, I was directed to Adi Basera, a house that the Indian government allowed the Great Andamanese to use when in town. It was a dilapidated building with peeling paint and dirty rooms; children and adults lounged listlessly in the courtyard. Someone brought out a plastic chair for me. I explained my quest in Hindi.

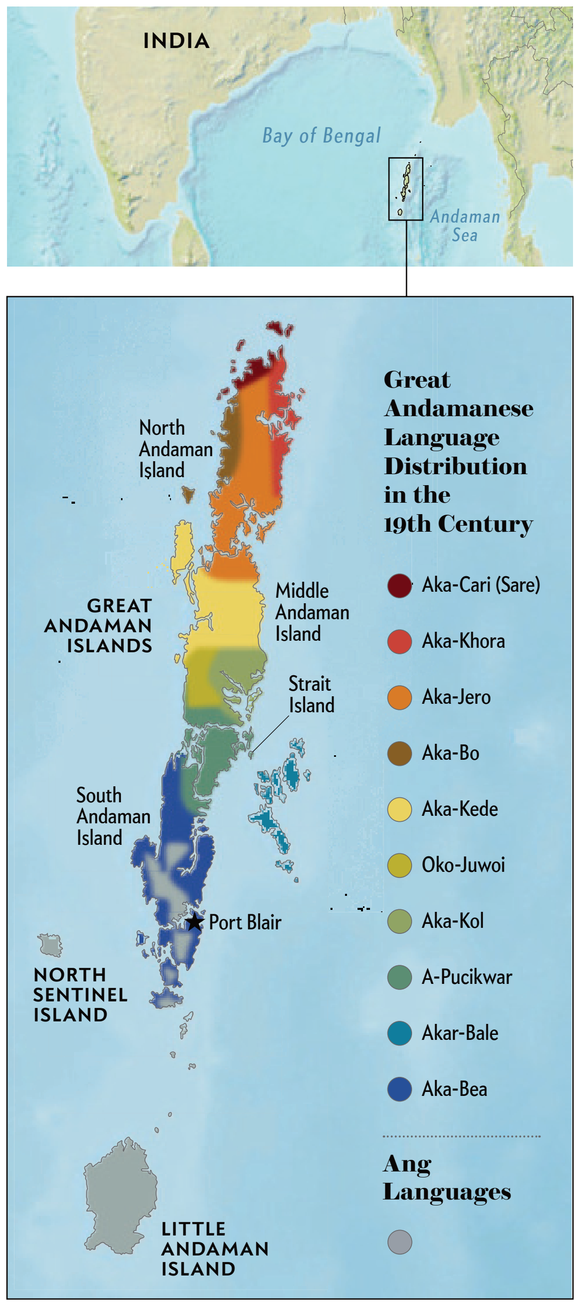
"Why have you come?" asked Boro Senior, an elderly woman. "We do not remember our language. We neither speak nor understand it." The entire community conversed primarily in Hindi, it turned out—a language essential for getting by in Indian society and the only one the children learned. As I probed, however, Nao Jr. confessed that he knew Jero, but because he had no one to speak it with, he was forgetting it. Boro Sr. turned out to be the last person to remember Khora, and Licho, then in her late 30s, was the last speaker of Sare, her grandmother's language. When conversing with one another, these individuals used what I call present-day Great Andamanese (PGA), a mixture of Jero, Sare, Bo and Khora—all languages of North Andaman.

When British officials established a penal colony at Port Blair in 1858, the rain forests of Great Andaman—comprising North, Middle and South Andaman, as well as some smaller islands nearby—were inhabited by 10 tribes of hunters and gatherers who seemed culturally related. The people of Great Andaman resisted the invaders, but their bows and arrows were no match for guns and, on one occasion, ship's cannons. Even more lethal were the germs that outsiders brought, to which the islanders had no immunity. In the 1960s, by which time the Andamans belonged to India, there were only 19 Great Andamanese left, living mainly in the forests of North Andaman. Indian authorities settled them on tiny Strait Island.

Another group of hunter-gatherers, the Jarawa, lived on South Andaman, and as the Great Andamanese died out, the Jarawa moved into their vacated territories in Middle Andaman. The Jarawa resisted

Languages of the Andaman Islanders

In 1858 British colonial authorities established a penal colony at Port Blair on the Andaman archipelago. At the time, the main island chain, Great Andaman, was inhabited by 10 groups speaking related languages, collectively called Great Andamanese. Other Indigenous islanders included the Jarawa on South Andaman, the Onge on Little Andaman and the people of North Sentinel, who are probably related to one another and speak languages of the Ang group.



Source: *The Andaman Islanders: A Study in Social Anthropology*, by A. R. Radcliffe-Brown, The University Press, 1922 (reference)

Map by Dolly Holmes

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The language structure offers a glimpse into a worldview in which the microcosm reflects the macrocosm. Everything connects to everything else.

contact—and attendant germs—until 1998 and now number about 450. Their culture had links to that of the Onge, who lived on Little Andaman and were subdued by the British in the 1880s. Apparently also related to the Jarawa were the people of North Sentinel Island. They continue to live in voluntary isolation, which they enforced in 2018 by slaying an American missionary.

My initial survey established that Great Andamanese languages were unrelated to those of the Jarawa and the Onge, which may constitute their own language family. Realizing that I had to document Great Andamanese before it was silenced, I returned with a team of students in 2005. It was shortly after the tsunami, and the authorities had evacuated all 53 of the Great Andamanese to a relief camp next to Adi Basera. They had survived, but their homes had been inundated and their possessions lost, and a sense of dislocation and grief hung in the air. In this situation, Licho gave birth to a boy named Berebe—a source of some joy. I learned that babies were named while in the womb. No wonder Great Andamanese names were gender-neutral!

At the camp I met octogenarian Boa Senior, the last speaker of Bo and a keeper of many songs. She would become very close to me. Great Andamanese youngsters had responded to mainstream Indians' contempt for Indigenous cultures by turning away from their heritage. Boa Sr. would hold my hand and not let me go because she was convinced that my presence alone, as a rare outsider who valued her language, would motivate the young ones to speak Great Andamanese. Still, I learned it mainly from Nao Jr. and Licho, whose interest in their languages was ignited by mine. Nao Jr., it turned out, knew a great deal about the local environment and Licho about etymology, often being able to tell me which word came from which language. I spent long hours with them at Adi Basera and on Strait Island, accompanying them wherever they went—lounging outside their huts, wandering in the jungle or fishing from the beach. The harder they tried to answer my questions, the more they retrieved from the depths of memory. I ended up collecting more than 150 Great Andamanese names for different fish species and 109 for birds.

British officials had observed that the Andamanese languages were a bit like links in a chain: members of neighboring Great Andaman tribes understood one another, but those speaking languages at opposite ends of the chain, in North and South Andaman, were mutually unintelligible. In 1887 British military administrator Maurice Vidal Portman published a comparative lexicon of four languages, as well as a few sentences with their English translations. And around 1920 Edward Horace Man compiled an exhaustive dictionary of Bea, a South Andaman language. These were significant records, but neither cracked the puzzle the grammar posed.

Nor could I. Somehow my extensive experience with all five Indian language families was no help. One time I asked Nao Jr. to tell me the word for "blood." He looked at me as if I were an utter fool and did not reply. When I insisted, he said, "Tell me where it is coming from." I replied, "From nowhere." Irritated, he repeated, "Where did you see it?" Now I had to make up something, so I said, "On the finger." The reply came promptly—"*ongtei!*"—and then he rattled off several words for blood on different parts of the body. If the blood emerged from the feet or legs, it was *otei;* internal bleeding was *etei;* and a clot on the skin was *ertei*. Something as basic as a noun changed form depending on location.

Whenever I got a break from my teaching and other duties, I would visit the Andamans, for weeks or months at a time. It took me a year of concerted study to see the language's pattern—and when I did, all the puzzle's scattered pieces fell into place. Very excited, I wanted to test my made-up sentences right away. I was at the Max Planck Institute for Evolutionary Anthropology in Leipzig, Germany, but I phoned Licho and said to her, "*a Joe-engio eole be.*" Licho was overwhelmed and gave me a cherished compliment: "You have learned our language, madam!"

My sentence was simply, "Joe sees you." Joe was a Great Andamanese youth, and *-engio* was "only you." My breakthrough was to realize that the prefix *e-,* which originally derived from an unknown word for an internal body part, had over eons morphed into a grammatical marker signifying any internal attribute, process or activity. So the act of seeing, *ole,* being an internal activity, had to be *eole*. The same prefix could be attached to *-bungoi,* or "beautiful," to form *ebungoi,* meaning internally beautiful or kind; to *sare,* for "sea," to form *esare,* or "salty," an inherent quality; and to the root word *-biinye,* "thinking," to yield *ebiinye,* "to think."

THE BODY CODE

THE GRAMMAR I was piecing together was based primarily on Jero, but a look through Portman's and Man's books convinced me that the southern Great Andamanese languages had similar structures. The lexicon consisted of two classes of words: free and bound. The free words were all nouns that referred to the environment and its denizens, such as *ra* for "pig." They could occur alone. The bound words were nouns, verbs, adjectives and adverbs that always existed with markers indicating a relation to other

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objects, events or states. The markers (specifically, *a-*; *er-*; *ong-*; *ot-* or *ut-*; *e-* or *i-*; *ara-*; and *o-*) derived from seven zones of the body and were attached to a root word, usually as a prefix, to describe concepts such as "inside," "outside," "upper" and "lower." For example, the morpheme *er-*, which qualified most anything having to do with an outer body part, could be stuck to *-cho* to yield *ercho,* meaning "head." A pig's head was thus *raercho.*

This conceptual dependency did not always indicate physical attachment. For example, if the pig's head were cut off for roasting, the marker *t-* for an inanimate object would be attached to *er-* to yield *ratercho;* it was no longer alive but still a pig's head. The suffix *-icho* indicated truly separable possessions. For example, *Boa-icho julu* meant "Boa's clothes."

Just as a head, a noun, could not conceptually exist on its own, the mode and effect of an action could not be severed from the verb describing the action. Great Andamanese had no words for agriculture or cultivation but a great many for hunting and fishing, mainly with a bow and arrow. Thus, the root word *shile,* meaning "to aim," had several versions: *utshile,* to aim from above (for example, at a fish); *arashile,* to aim from a distance (as at a pig); and *eshile,* aiming to pierce.

Also inseparable from their prefixes, which endowed them with meaning, were adjectives and adverbs. For example, the prefix *er-*, for "external," yielded the adjective *erbungoi,* for "beautiful"; the verb *eranye,* meaning "to assemble"; and the adverb *erchek,* or "fast." The prefix *ong-*, the zone of extremities, provided *ongcho,* "to stitch," something one did with fingers, as well as the adverb *ongkochil,* meaning "hurriedly," which usually applied to movements involving a hand or foot. Important, too, was the morpheme *a-*, which referred to the mouth and, more broadly, to origins. It contributed to the nouns *aphong,* for "mouth," and *Aka-Jero,* for "his Jero language"; the adjectives *ajom,* "greedy," and *amu,* "mute"; the verbs *atekho,* "to speak," and *aathitul,* "to keep quiet"; and the adverb *aulu,* "prior to."

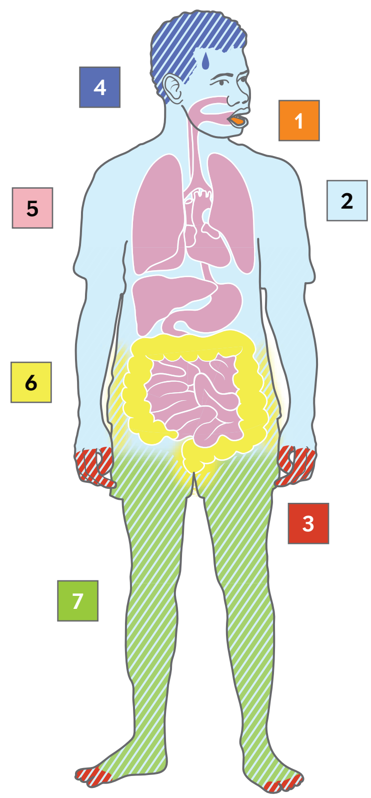
These studies established that the 10 original Great Andamanese languages belonged to a single family. Moreover, that family was unique in having a grammatical system based on the human body at every structural level. A handful of other Indigenous languages, such as Papantla Totonac, spoken in Mexico, and Matsés, spoken in Peru and Brazil, also used terms referring to body parts to form words. But these terms had not morphed into abstract symbols, nor did they spread to every other part of speech.

Most significant, the language family seems to be truly archaic in origin. In a multistage process of evolution, words describing diverse body parts had changed into morphemes referring to different zones and fused with content words to yield meaning. Along with the genetic evidence, which indicates the Great Andamanese lived in isolation for tens of thousands

Zones of the Human Body

The structure of Great Andamanese languages derives from a conceptual division of the human body into seven zones. Each region is designated by a marker that attaches to content-bearing root words to form nouns, verbs and other aspects of speech. In a prehistoric time, parts of the body (such as internal organs) became abstracted to concepts (such as "inner") pertaining to the entire world. In consequence, the marker for a zone precedes every object, attribute or activity related to that part or concept. This structural principle is evident at every level of grammar.

ZONE	MARKER	BODY PART SEMANTICS
1	*a-*	Related to mouth/origins
2	*er-*	External body parts/outer
3	*ong-*	Extremities
4	*ut-/ot-*	Protrusions, bodily products, part-whole relations/upper
5	*e-/i-*	Internal organs/internal
6	*ara-*	Sexual organs and sides/round shapes
7	*o-*	Related to legs/lower/end result or termination



Graphic by Mesa Schumacher

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Words Derived from Body Zones

Great Andamanese languages have two classes of words: free and bound. The free words pertain to nature and can exist without markers. The bound words are nouns, adjectives, verbs and adverbs that always occur with markers for zones of the human body. These markers, usually attached as prefixes, indicate relationships with other objects, events, or states. For some markers, like *e-* of zone 5, the relationship with the corresponding word and its meaning is evident, but at other times, as with *o-* of zone 7, it can be obscure.

In a protracted process of evolution, words describing body parts became abstracted into word segments referring to different zones and fused with content words to yield diverse meanings. This grammatical structure, along with genetic evidence indicating that the inhabitants of Great Andaman were isolated from other peoples for tens of thousands of years, points to the antiquity of the language family. It also suggests that these early humans conceived of the world around them through their bodies.

ZONE	MARKER	BODY PART	NOUN	ADJECTIVE	VERB	ADVERB
1	*a-*	Related to mouth/origins	***aphong*** mouth ***aphup*** saliva	***ajom*** greedy ***amu*** mute	***aathitul*** keep quiet ***akopho*** sprout	***aulu*** prior to
2	*er-*	External body parts/outer	***erphile*** teeth ***ercho*** head	***erchek*** angry ***erbungoi*** beautiful	***erikak*** aim at ***eranye*** assemble	***erninuchoich*** embrace tightly
3	*ong-*	Extremities	***ongkara*** nails ***ongkoro*** palm	***ongtoplo*** having disabled hands	***ongcho*** stitch ***ongtujuro*** trembling of hands	***ongkochil*** hurriedly
4	*ut-/ot-*	Protrusions, bodily products, part-whole relations/upper	***otbech*** hair ***utkhirme*** sweat	***utbelo*** wide ***utkobolo*** bald	***otbolo*** peel off ***utthu*** be born	***utkotcho*** above head, heavenly
5	*e-/i-*	Internal organs/internal	***esudu*** small intestine ***ie*** pain	***ekhir*** hot ***ebungoi*** kind	***ebiinye*** think ***eole*** see	***ekotra*** inside
6	*ara-*	Sexual organs and sides/round shapes	***arathomo*** buttocks ***aratolo*** large intestine	***aratom*** old ***araphetkheto*** having a round belly	***arapho*** fell a tree (by cutting into its round side)	***arabalo*** behind
7	*o-*	Related to legs/lower/end result or termination	***omoto*** leg ***orongo*** ankle	***ophelanya*** slippery	***olam*** tire ***ochorn*** make a nest	***okara*** at sundown

of years, the grammar suggests that the language family originated very early—at a time when human beings conceptualized their world through their bodies. The structure alone provides a glimpse into an ancient worldview in which the macrocosm reflects the microcosm, and everything that is or that happens inextricably connects to everything else.

ANCESTORS, BIRDS

ONE MORNING on Strait Island, I heard Boa Sr. talking to the birds she was feeding. I listened for quite a while from behind a door and then emerged to ask her why she was speaking to them.

"They're the only ones who understand me," she replied.

"How come?" I asked.

"Don't you know they're our ancestors?"

I tried to suppress an astonished laugh, but Boa heard me. "Yes, they are our ancestors," she asserted. "That's why we don't kill or hunt them. You should go ask Nao Jr.; he might know the story."

Nao did not remember right away, but a few days later he narrated the tale of a boy named Mithe who went fishing. He caught a squid, and while cleaning it on the beach, he was swallowed by a *Bol,* a big fish. His friends and family came searching for him and realized that a *Bol* had eaten him. Phatka, the cleverest of the youths, traced the dirty track left by the fish and found the *Bol* in shallow water with its head in the sand. It was very big, so Phatka, Benge, and others called loudly for Kaulo, the strongest one, who arrived and killed the fish.

Mithe emerged alive, but his limbs were numb. They lit a fire on the beach and warmed him by it, and

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once he had recovered, they decided to eat the fish. They put it on the fire to roast. But they had neglected to properly clean the fish, and it burst—turning everyone present into birds. From that point on the Great Andamanese had a particular affinity with *Mithe,* the Andaman Cuckoo Dove; *Phatka,* the Indian Crow; *Benge,* the Andaman Serpent Eagle; *Kaulo,* the White-Bellied Sea Eagle; *Celene,* the Crab Plover; and other birds they regarded as ancestors.

In the Great Andamanese view of nature, the foremost distinction was between *tajio,* the living, and *eleo,* the nonliving. Creatures were *tajio-tut-bech,* "living beings with feathers"—that is, of the air; *tajio-tot chor,* "living beings with scales," or of the water; or *tajio-chola,* "living beings of the land." Among the land creatures, there were *ishongo,* humans and other animals, and *tong,* plants and trees. These categories, along with multiple attributes of appearance, motion and habits, made for an elaborate system of classification and nomenclature that I documented for birds in particular. Sometimes the etymology of a Great Andamanese name bore a resemblance to the English one. For example, *Celene,* made up of root words for "crab" and "thorn," was so named because it cracks and eats crabs with its hard, pointed beak.

The exceedingly detailed understanding of the natural environment held by the Great Andamanese people—Nao Jr. named at least six varieties of seashore and more than 18 kinds of smell—indicates a culture that observed nature with deep love and acute interest. Seeing nature as a whole, they sought to examine the interweaving of forces building up this whole. Space was a cultural construct, defined by the movement of spirits, animals and humans along vertical and horizontal axes. In the worldview of the Great Andamanese, space and all natural elements in it—the sun, the moon, the tide, the winds, the land and the forest—together constituted the cosmos. In this holistic view, birds, other creatures and spirits were all interrelated and integral to the concept of space.

Time, too, was relative, categorized according to natural events such as the blossoming of seasonal flowers, the availability of honey—the honey calendar, one might call it—the movement of the sun and the moon, the direction of winds, the availability of food resources, and the best time for hunting fish or other animals. Thus, when the *koroiny auro* flower blooms, the turtles and fish are fat; when the *bop taulo* blooms, the *bikhir, liot* and *bere* fish are abundant; when the *loto taulo* blooms, it is the best time for catching *phiku* and *nyuri* fishes; and when the *chokhoro taulo* blooms, the pigs are at their fattest, and it is the best time to hunt them.

Even "morning" and "evening" were relative, depending on who experienced them. To say, for instance, "I will visit you tomorrow," one would use *ngambikhir,* for "your tomorrow." But in the sentence "I will finish this tomorrow," the word would be *thambikhir,* "my tomorrow." Time depended on the perspective of whoever was involved in the event.

The myths of the Great Andamanese indicated that their earliest ancestors resided in the sky, as in another story Nao Jr. related to me. The first man, emerging from the hollow of a bamboo, found water, tubers, fine clay and resin. He molded a clay pot, lit a fire with the resin, boiled the tubers in the pot and enjoyed a hearty meal. Then he crafted a clay figure and left it over the fire. To his astonishment and joy, it turned into a woman. They had many children and were very happy. After a long time on Earth, the couple departed for a place above the clouds, snapping all ties with this world.

Tears ran down Nao Jr.'s cheeks as he narrated this creation tale, which featured all the elements of life: water, fire, earth, space and air. For this lonely man—his wife had left him years back for another man—creating a partner according to one's wishes was the ultimate romantic fable. When I'd first asked him for stories, he had said he hadn't heard any in 40 years and had none for me. But over many evenings, with crickets chirping and frogs calling outside, he told me 10 precious stories—almost unheard of for a language on the verge of extinction. Perhaps one reason we bonded so much was that we were both *raupuch*—someone who has lost a sibling. Nao Jr. was shocked to learn that neither English nor any Indian language has such a word. "Why?" he asked. "Don't you love your brothers and sisters?"

Nao Jr. left this world in February 2009. In his untimely death, he took with him a treasure trove of knowledge that can never be resurrected and left me a *raupuch* all over again. Boro Sr. passed away that November and Boa Sr. in January 2010, leaving her voice in several songs. Licho died in April 2020. At present only three people—Peje, Golat and Noe—speak a language of the Great Andamanese family, in their case Jero. They are all more than 50 years old and suffer from a variety of ailments. The entire language family is at imminent risk of extinction.

Of the roughly 7,000 languages spoken by humans today, half will fall silent by the end of this century. Survival in an era of globalization, urbanization and climate change forces Indigenous communities to replace their traditional ways of life and languages with those of the dominant society. When the older generation can no longer teach the tongue to the younger ones, a language is doomed. And with every language lost, we lose a wealth of knowledge about human existence, perception, nature and survival. To give the last word to Boa Sr.: "All is gone, nothing is left—our jungles, our water, our people, our language. Don't let the language slip away! Keep a hold on it!" SA

FROM OUR ARCHIVES

Talking through Time. Christine Kenneally; September 2018.

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EPIDEMIOLOGY

Dead Heat

The greyhound racing industry has been implicated in the evolution of drug resistance in hookworms—which can infect dogs and humans

By Bradley van Paridon



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A RACING GREYHOUND peers out of its cage at a kennel in Florida in the summer of 2018.

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IN 2017 RAY KAPLAN, A PARASITOLOGIST AND VETERINARIAN THEN AT THE UNIVERSITY OF GEORGIA, started receiving e-mails from colleagues around the U.S. asking for help with resistant parasitic infections in dogs. The parasites were hookworms, a group of roundworm species that target animals and humans. Kaplan specializes in livestock animals, not pets. But the infections described in the e-mails sounded like cases of drug resistance, which he had studied in livestock parasites. The overuse of antiparasitic drugs in sheep and goats and the trade of these animals have led to widespread drug resistance across the globe. If drug-resistant parasites were spreading in dogs, too, that would be worrying. Kaplan had no idea just how big the problem was, however, until he started studying it.

Through a series of studies published over the past few years, Kaplan and his colleagues have traced the origin, evolution and spread of drug-resistant hookworms in dogs. Their findings implicate the greyhound racing industry in the rise of these superparasites. Once a national pastime, greyhound racing is now nearly extinct in the U.S. But it may have left a dangerous legacy that poses a risk to all dogs. The researchers' discoveries also offer a cautionary tale for the management of human parasite infections.

Parasitic roundworms are ubiquitous in the animal kingdom. Hookworms are named for their hook-shaped mouthparts, which they use to latch on to a host's intestinal wall and feed on its blood. In dogs, the most common species is *Ancylostoma caninum*. Adult hookworms live in the gut, and their eggs are spread through feces. Dogs can get infected when they come into contact with the larvae while walking or playing in contaminated areas or when they ingest larvae-ridden feces.

A. caninum infection is known by veterinarians to be potentially fatal for puppies. The worms consume so much blood that young animals can die from blood loss. A puppy is also at risk because high numbers of larvae can pass through the milk of its infected mother.

Hookworm is typically treated with one of three classes of antiparasitic drugs: benzimidazoles, macrocyclic lactones or tetrahydropyrimidines. To find out whether dog hookworms are resistant to any of these drugs, Kaplan began a series of laborious in vitro and in vivo tests on hookworm samples from three dogs with stubborn infections, including one greyhound named Worthy.

Greyhounds are notorious for developing resistant hookworm infections. For years veterinarians blamed this tendency on *A. caninum*'s ability to lie dormant in its host's tissue and remerge after the original infection had cleared, a phenomenon known as larval leak. But Kaplan's initial results, published in 2019, showed that the worms in the three dogs he tested were resistant to all three main classes of drugs used to treat hookworm infections. Kaplan also tested for benzimidazole tolerance in worms from Worthy's housemate and from another retired greyhound, both of whom had histories of stubborn infections, and found that they were resistant.

These findings, along with the greyhound's hookworm reputation, led Kaplan to suspect something was happening on greyhound farms. What he found on further investigation was the perfect combination of factors to promote the evolution of drug resistance.

IN THE EARLY 1990S greyhound racing in the U.S. was at its peak. In 1993 greyhounds were competing at dozens of tracks throughout 19 states, and the National Greyhound Association reported that 39,139 new dogs were born on greyhound farms that year. The sport began to decline in the early 2000s because of pressure from animal welfare organizations and the decision by many states to ban it. By 2020 the number of new greyhounds born on farms had dropped to 4,898 a year. Today dog racing is illegal in 42 states, and just two tracks remain active, although roughly 100 breeding farms are still operating.

During their heyday greyhound farms raised hundreds of dogs at a time and treated them regularly with dewormers—regardless of whether they had an active infection—to keep them in peak health. "That's exactly what you don't want to do if you want to avoid resistance," says hookworm expert John Hawdon of George Washington University, who independently reported drug-resistant hookworms in another former racing greyhound in 2019.

Constant drug exposure means any worms that survive have a reproductive advantage and dominate the

Scott McIntyre (*preceding pages*)

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next generation. Moreover, the exercise pens for these dogs are set up on sand or dirt, which can be the perfect habitat for developing hookworm larvae. After dogs defecate in the pens, the hookworm eggs hatch, and the larvae eventually molt, reaching their infective stage within five to 10 days. Thus, every day when the greyhounds go out to run, they are exposed to resistant hookworm larvae from other dogs, and they seed the environment with resistant hookworms of their own.

(Veterinarians are encountering a similar but less severe situation with canine heartworm. Pet dogs typically receive regular preventive treatments for this parasite. Although drug resistance has been detected in these worms in some regions of the southern U.S., there are still effective treatments, and the resistance trait does not appear to have spread, probably because of differences in the biology and epidemiology of this parasite compared with hookworms. Kaplan says owners should keep their dogs on heartworm prevention and get a yearly test.)

To confirm that hookworm drug resistance was originating on greyhound farms, Kaplan carried out a second study, published in 2021, in which he sampled worms from two greyhound adoption kennels in Birmingham, Ala., and Dallas, Tex., and an active racing kennel in Sanford, Fla., and tested them for resistance. Samples from the Florida kennel were collected from the ground, making it impossible to know which dog they came from. But dogs at this kennel came from facilities in four other states—Colorado, Arkansas, Oklahoma and West Virginia—meaning any worms testing positive as resistant may be present in those locations as well. The results replicated what Kaplan had found two years earlier in Worthy: hookworms on the farms had high levels of resistance to all three drug classes. Worms that are resistant to benzimidazoles have up to three known single-nucleotide mutations in their DNA that confer resistance. These changes, each to one DNA building block, occur at three locations in the sequence of a single gene, making it possible to quickly screen worms' DNA and find out whether they are resistant to benzimidazoles. In the 2021 study of greyhound farms, 99 percent of the samples sequenced had one of the three resistance mutations.


Ancylostoma caninum

Dennis Kunkel Microscopy/Science Source

THE PRESENCE OF DRUG-RESISTANT hookworms at greyhound farms, Kaplan realized, poses a threat to the pet population. As the racing industry began its decline in the early 2000s, organizations sprang up to rehome the dogs, leading to thousands of greyhounds being adopted across the country in the past two decades. Greyhounds infected with drug-resistant hookworm could pass the parasites to other pet dogs.

Traditionally vets didn't pay much attention to hookworm infections in dogs, because there weren't that many cases. When doctors did see them, they prescribed drugs, but little follow-up occurred, and persistent infections were blamed on larval leak.

Then dog parks started gaining in popularity. Between 2009 and 2019 the number of such parks in the 100 largest U.S. cities increased by 74 percent. These spaces provide the perfect environment for the spread of parasites. As many as 500,000 hookworm eggs can be left in a single dropping from an adult canine, and once eggs and larvae are present in a park, it is nearly impossible to get rid of them. Two studies from 2020 and 2021 found that dogs visiting dog parks had a 70 percent higher prevalence of hookworm infections compared with the overall population.

Having established that greyhound farms were generating drug-resistant hookworms and that at least some pet dogs were infected with them, Kaplan needed a way to determine just how common the superparasites had become in the general dog population. He teamed up with John Gilleard and his laboratory at the University of Calgary in Canada. Gilleard has successfully adapted a DNA-sequencing technique that can screen hundreds of hookworm eggs from a single dog simultaneously for resistance mutations.

After sequencing fecal samples known to contain hookworms procured from diagnostic labs in Tennessee, Massachusetts, Illinois and California, the researchers were shocked. "We thought maybe 5 or 10 percent prevalence would be high," Kaplan says. But to their astonishment, they found that one of the known resistance mutations was present in 49 percent of the fecal samples, and a novel mutation, which they confirmed also conferred resistance, was present in 31 percent. These results, published in March in *PLOS Pathogens,* suggest that roughly

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GREYHOUNDS bred for racing are raised under conditions that have promoted the rise of drug-resistant hookworms.

Scott McIntyre for the *Washington Post* via Getty Images

50 percent of dogs in the U.S. with hookworm infections are carrying worms resistant to benzimidazole drugs. Although genetic screens for drug resistance are not possible for the other drug classes, Kaplan thinks it is likely that some of the worms will be resistant to them, too.

JUST HOW BIG A PROBLEM drug-resistant parasites are depends on who gets infected. For most dogs, resistant hookworms are not fatal, and barring reinfection, the worms will eventually die. But the more these worms circulate in the population, the greater the risk of death for puppies and other vulnerable individuals.

A. caninum also can infect humans. The worms cause a painful condition called cutaneous larva migrans, in which larvae burrow in the skin and sometimes the eyes and wander around looking for the molecular cues that indicate they're in the right host. There are also rare cases of *A. caninum* causing severe gastrointestinal symptoms in humans, Hawdon says, a condition called eosinophilic enteritis. He noted some recent but unconfirmed reports of people with patent *A. caninum* infections, meaning reproductive adult parasites were detectable in their bodies, and points out that even if these particular cases remain unverified, "it is not inconceivable that it will happen in the future." Because the same drug classes are used for hookworm infections in both dogs and humans, the rise of drug-resistant worms will complicate all treatment.

Although animal-to-human transmission of hookworm is generally considered uncommon, there are no reliable data on the number of cases in the U.S. Most reported infections in people are from travelers returning to the U.S. from tropical locations, particularly those where sanitation and animal husbandry conditions are poor. Zoonotic transmission may be underestimated, however. When Kaplan raised the issue of drug-resistant hookworm with the Centers for Disease Control and Prevention, he found little interest because cutaneous larva migrans is not something they monitor or track. But data from the other side of the world suggest there may be cause for concern: in 2020 researchers in Australia found that, contrary to prior belief, a hookworm species that commonly infects cats and dogs in Southeast Asia does infect people, too, and in some areas it accounts for up to 46 percent of hookworms found in humans.

Despite these worrying trends, Kaplan and Hawdon emphasize that we shouldn't blame the greyhounds. "It's a shame to stigmatize them because as the last of these tracks die, there's going to be even more of these dogs to adopt," Hawdon says. Resistant worms are already circulating in the U.S. canine population, meaning all dogs can catch and spread them. Putting the risk to other dogs into perspective, Kaplan argues that although hookworms are present in most greyhounds, other breeds are the likely carriers when it comes to pet exposure. "There are only a few thousand greyhounds that are being adopted in a year," he says. But "there are 100 million dogs in the U.S.," and we know that the prevalence of the parasite in that population is about 4 percent.

Veterinarian Pablo David Jimenez Castro worked with Kaplan as a graduate student on the greyhound studies and is now co-chair of the American Association of Veterinary Parasitologists Hookworm Task Force. According to him, the best thing dog owners can do to protect their pets from hookworm, whether they adopt a grey-

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hound or not, is to have their vet administer fecal egg tests for worms four times a year. If your dog has worms, be diligent with the treatment prescribed by the vet, and, most important, clean up after your pet. "Pick up the poop as soon as you can," Jimenez Castro says. If owners prevent the infected dog from getting reinfected or passing the parasite to any other pets in the home, the worms will run their course and die. "[Dog owners] want to basically burn the backyard, the lawn, all of it just because they know that the dogs have hookworms," Jimenez Castro says. But disposing of feces within 48 hours is enough to get any eggs they contain away from the area before they hatch and become infective.

Likewise, Jimenez Castro says, owners shouldn't be afraid of dog parks. "In big cities [such as] New York, the only place for a dog to be a dog is going to be the dog park," he notes. But owners need to understand the risk and stay on top of checkups with the vet. Unfortunately, there is little that cities can do to eliminate hookworm in parks. Once larvae have made it to the grass and soil, they are impossible to find and kill.

In the meantime, researchers need to monitor other species for signs of infection with these superparasites. Our inability to treat the environment for worms means there is potential for wild canids that frequent urban spaces, such as coyotes and foxes, to pick up resistant worms as well. Wild canines range much farther than their domesticated counterparts and are not regularly treated or monitored for parasites, so they may be invisible spreaders of the resistant worms.

The rise of drug-resistant hookworm in dogs serves as a warning of what could happen with other species of roundworms that infect humans. Several serious, neglected tropical diseases in humans are caused by roundworms, including river blindness, lymphatic elephantiasis and ascariasis. Because these worms are genetically similar to dog hookworms and are treated with the same drugs, they can develop similar mutations that confer drug resistance. For the past decade public health officials, nongovernmental organizations and pharmaceutical companies have carried out mass drug administration programs in communities affected by the worms that cause these diseases. They have delivered millions of doses of antiparasitic drugs, mainly to children, who suffer the most from morbidity and developmental delays caused by heavy worm infections, with great success. Lymphatic elephantiasis was deemed eradicated in several countries after such programs were implemented.

Already there are reports of the same benzimidazole-resistance mutations appearing in human roundworms. Gilleard cautions that drugs alone cannot eliminate parasites, and, as the greyhound example shows, drug resistance can appear in one population and easily spread to others. Widespread surveillance for resistance—which is now possible with modern DNA sequencing technologies—is essential, he says. Without it, drug resistance will spread undetected before control programs can adapt, leading to a wormier world for everyone. SA

AS DOG RACING has declined, the adoption of retired greyhounds is thought to have spread drug-resistant hookworm into household dogs.

Scott McIntyre for the *Washington Post* via Getty Images

FROM OUR ARCHIVES

A New Strain of Drug-Resistant Malaria Has Sprung Up in Africa. Thomas Hall; ScientificAmerican.com, January 2, 2021.

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MATHEMATICS

The Most Bo

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ring Number

Prime numbers and powers of 2 are considered fascinating,
but in fact all numbers can be split into two camps: interesting and boring

By Manon Bischoff

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Manon Bischoff is a theoretical physicist and editor at *Spektrum,* a partner publication of *Scientific American.*



WHAT IS YOUR FAVORITE NUMBER? FOR MANY PEOPLE, IT MAY BE AN irrational number such as pi (π), Euler's number (*e*) or the square root of 2. Even among the natural numbers (positive integers), there are values that feel significant because we encounter them in a wide variety of contexts: the seven dwarfs, the seven deadly sins, the unlucky number 13—and 42, which was popularized by the 1979 novel *The Hitchhiker's Guide to the Galaxy,* written by Douglas Adams.

What about a larger value such as 1,729? The number certainly doesn't seem particularly exciting. It's not a prime number or a power of 2 or the square of some other number. The digits don't seem to follow any obvious pattern. That's what mathematician Godfrey Harold Hardy thought when, in 1918, he got into a cab in London with the identification number 1729. At the time, he was on his way to visit his ailing colleague Srinivasa Ramanujan in the hospital, and he mentioned the "boring" cab number when he arrived. He told Ramanujan he hoped it wasn't a bad omen. Ramanujan immediately contradicted his friend: "It is a very interesting number; it is the smallest number expressible as a sum of two cubes in two different ways."

You may wonder: Is there any number that is not interesting in some way? The question quickly leads to a paradox: if there is a value *n* that has no exciting properties, this very fact makes it special. But there is a way to determine the interesting properties of a number fairly objectively—and to mathematicians' great surprise, research in 2009 suggested that natural numbers can be divided into two sharply defined camps: exciting values and boring ones.

A comprehensive encyclopedia of number sequences provides a means for investigating these two opposing categories. Mathematician Neil Sloane had the idea for such a compilation in the 1960s, when he was writing his doctoral thesis. He had to calculate the height of values in a type of graph called a tree network and came across a sequence of numbers: 0, 1, 8, 78, 944 … He didn't know how to calculate the numbers in this sequence exactly, and he wanted to know whether his colleagues had already come across a similar sequence. But unlike for logarithms or formulas, there was no registry for sequences of numbers. And so, 10 years later, Sloane published his first encyclopedia, *A Handbook of Integer Sequences,* which contained about 2,400 sequences that also proved useful in making certain calculations. The book was met with enormous approval. "There's the Old Testament, the New Testament and the *Handbook of Integer Sequences*," wrote one enthusiastic reader, according to Sloane.

In the years that followed, Sloane's catalog of number sequences got bigger. In 1995 the mathematician, together with his colleague Simon Plouffe, published *The Encyclopedia of Integer Sequences,* which contained some 5,500 entries. The list has been growing ever since. As of March 2023, the Online Encyclopedia of Integer Sequences (OEIS) contained more than 360,000 items. Anyone can make a submission—they just have to say how the sequence was generated and why it's interesting, and provide examples explaining the first few terms. Reviewers then check the entry, and if it meets their criteria, it gets published.

Besides well-known sequences such as the prime numbers (2, 3, 5, 7, 11 …), the powers of 2 (2, 4, 8, 16, 32 …) and the Fibonacci sequence (1, 1, 2, 3, 5, 8, 13 …), the OEIS catalog contains exotic entries such as the number of ways to build a stable tower from *n* two-by-four-studded LEGO blocks (1, 24, 1,560, 119,580, 10,166,403 …) and the "lazy caterer's sequence" (1, 2, 4, 7, 11, 16, 22, 29 …), which is the maximum number of pieces you can slice a pie into with *n* cuts. The collection is intended to be an objective compilation of all sequences, which makes it useful for studying the popularity of numbers—the more often a number appears in the list, the more interesting it is.

At least that was the logic of Philippe Guglielmetti, who runs the French-language science blog Dr. Goulu. In one post, Guglielmetti recalls a math teacher's claim that 1,548 is an arbitrary number with no special properties. In fact, this number appears 326 times in the OEIS catalog. One example: it shows up as an "eventual period of a single cell in rule 110 cellular automaton in a cyclic universe of width *n*." Hardy was also wrong when he said the cab number 1729 was boring: 1,729 appears 918 times in the database (and also frequently in episodes of the television show *Futurama*).

Guglielmetti went in search of really boring numbers: those that appear in the OEIS catalog only very rarely or, like 20,067, not at all. As of this past March, 20,067 was the smallest number that did not appear in any of the OEIS's stored number sequences. (This is because the database stores only the first 180 or so characters of a number sequence, however; otherwise every number would appear in the OEIS's list of posi-

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tive integers.) There are just six entries for 20,068.

Guglielmetti went on to plot the sequence of boring numbers graphically. He found a cloud of points in the form of a broad curve that slopes toward large values. This is not surprising insofar as only the first members of a sequence are stored in the OEIS catalog. What is surprising, however, is that the curve consists of two bands that are separated by a clearly visible gap. The gap means that any given natural number appears either particularly frequently or extremely rarely in the OEIS database.

Fascinated by this result, Guglielmetti turned to mathematician Jean-Paul Delahaye of the University of Lille in France, who regularly writes for *Pour la Science, Scientific American*'s French-language partner publication. He wanted to know whether experts had already studied this phenomenon. They had not, so Delahaye took up the topic with his colleagues Nicolas Gauvrit, also at Lille, and Hector Zenil of the University of Cambridge. They used results from algorithmic information theory, which measures the complexity of an expression by the length of the shortest algorithm that describes the expression. For example, an arbitrary five-digit number such as 47,934 is more difficult to describe ("the sequence of digits 4, 7, 9, 3, 4") than 16,384 (2^{14}). According to a theorem from information theory, numbers with many properties usually also have low complexity. That is, the values that appear frequently in the OEIS catalog are the most likely to be simple to describe. Delahaye, Gauvrit and Zenil were able to show that information theory predicts a trajectory for the complexity of natural numbers that is similar to the one shown in Guglielmetti's curve. But this does not explain the gaping hole in that curve, known as Sloane's gap, after Neil Sloane.

The three mathematicians suggested that the gap arises from social factors such as preferences for certain numbers. To substantiate this, they ran what is known as a Monte Carlo simulation: they designed a function that maps natural numbers to other natural numbers—and does so in such a way that small numbers are output more often than larger ones. The researchers put random values into the function and plotted the results according to their frequency. The end product was a fuzzy, sloping curve similar to that of the data in the OEIS catalog. And just as with the information theory analysis, there was no trace of a gap.

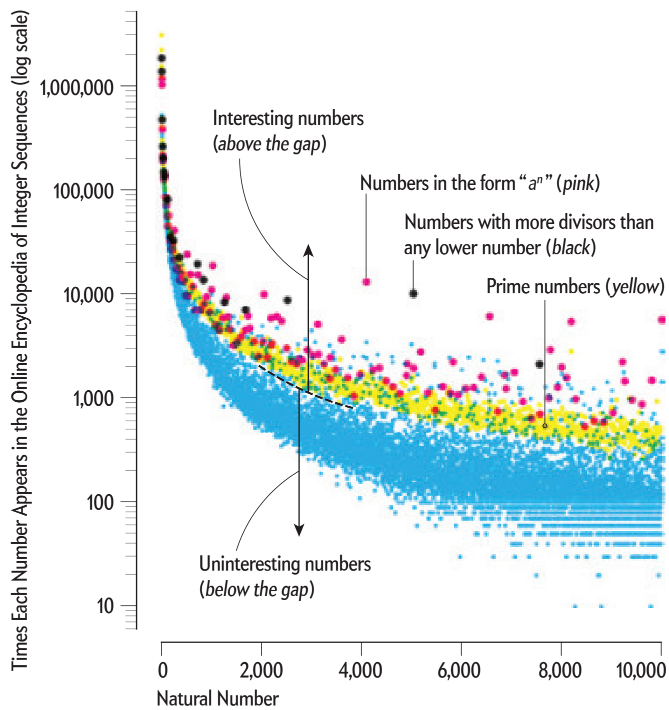
To better understand why the gap occurs, one must look at which numbers fall into which band. For values up to about 300, Sloane's gap is not very pronounced. Only for larger numbers does the gap open up significantly: about 18 percent of all numbers between 300 and 10,000 are in the "interesting" band, and the remaining 82 percent are "boring" values. As it turns out, the interesting band includes about 95.2 percent of all square numbers and 99.7 percent of prime numbers, as well as 39 percent of numbers with many prime factors. These three classes account for nearly 88 percent of the interesting band. The remainder consists of values with striking properties, such as 1,111 or the formulas $2^n + 1$ and $2^n - 1$.

According to information theory, the numbers that should be of particular interest are those that have low complexity, meaning they are easy to express. But if mathematicians consider certain values more exciting than others of equal complexity, this can lead to Sloane's gap, as Delahaye, Gauvrit and Zenil argue. For example: $2^n + 1$ and $2^n + 2$ are equally complex from an information theory point of view, but only values of the first formula are in the interesting band. Those values appear in many different contexts because they allow prime numbers to be studied.

The split into interesting and boring numbers, then, seems to result from judgments we make, such as attaching importance to prime numbers. If you want to give a really creative answer when asked what your favorite number is, you could always say, "20,067." SA

A Gap of Judgment

Examination of the frequencies of natural numbers in the Online Encyclopedia of Integer Sequences (OEIS) shows that two types of numbers can be identified: interesting values that appear frequently (*upper band*) and boring ones (*lower band*). The horizontal axis measures the natural numbers. The vertical axis represents how many times a particular number is mentioned in the OEIS catalog. As the values get larger, around 300, a hole opens up. Mathematicians have argued that the so-called Sloane's gap occurs because we consider certain values more exciting than others even if they have equal complexity.



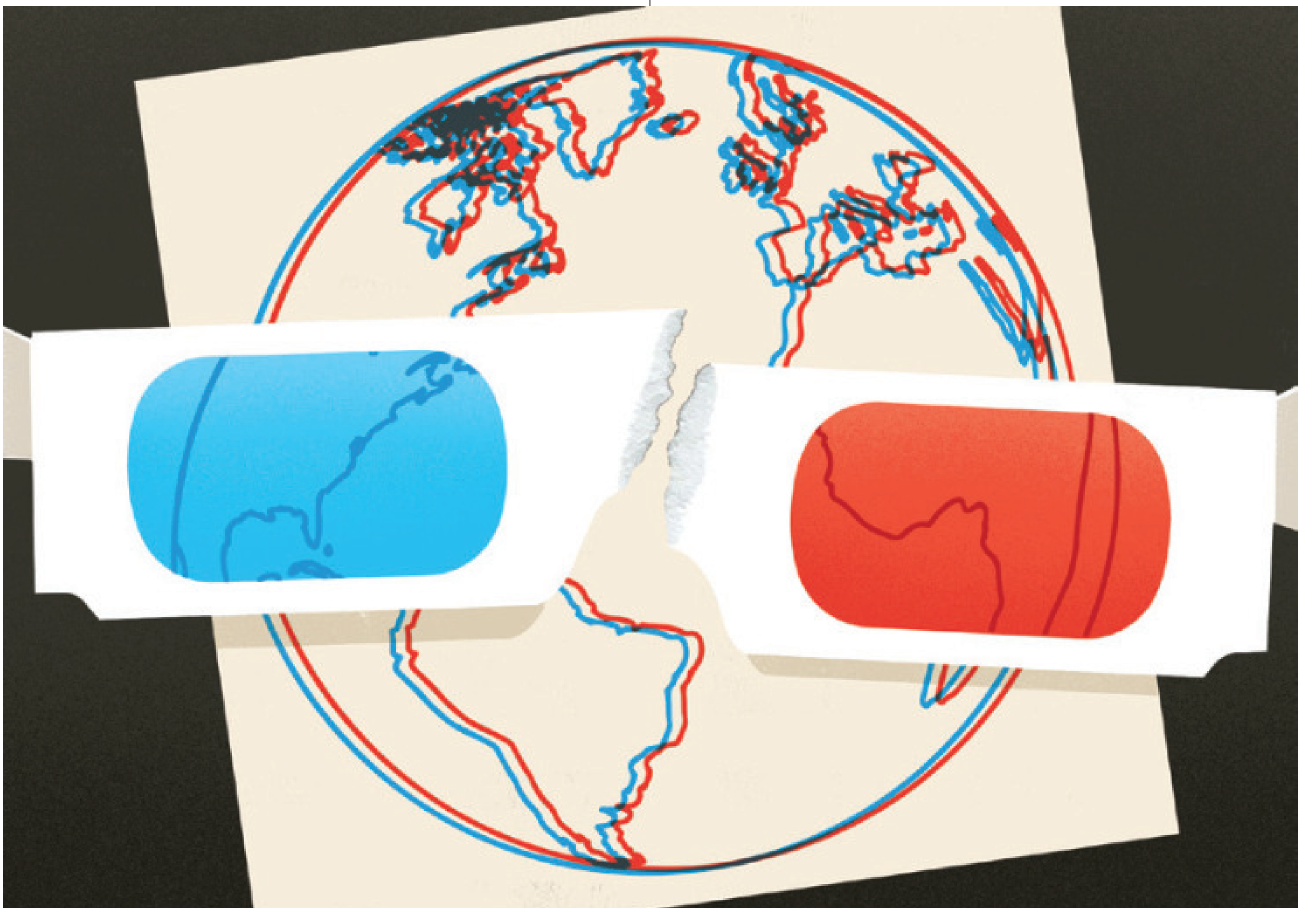
Philippe Guglielmetti (*graphic*), restyled by Jen Christiansen

FROM OUR ARCHIVES

Numbers Game. Kelsey Houston-Edwards; September 2019.

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Divided Mindset

Conservatives tend to believe that strict divisions are an inherent part of life. Liberals do not

By Jer Clifton

Disagreement has incapacitated our politics and our collective ability to get things done. But where do these conflicts come from? A split between liberals and conservatives, many might say. But underlying that division is an even more fundamental fissure in the way people view the world.

In politics, researchers usually define "conservativism" as a general tendency to resist change and tolerate social inequality. "Liberalism" means a tendency to embrace change and reject inequality. Political parties evolve with time—Democrats were the conservative party 150 years ago—but the liberal-conservative split is typically recognizable in a country's politics. It's the fault line on which political cooperation most often breaks down.

Psychologists have long suspected that a few fundamental differences in worldviews might underlie the conservative-liberal rift. Forty years of research has shown that, on average, conservatives see the world as a more dangerous place than liberals do. This one belief seemed to help explain many American conservative stances in policy disagreements, such as support of gun ownership, border enforcement, and increased spending on police and the military—all of which, one can argue, are meant to protect people from a threatening world.

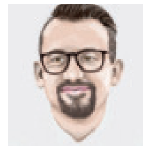
But new research by psychologist Nick Kerry and me at the University of Pennsylvania contradicts that long-standing theory. We find instead that the main difference between the left and the right is whether people believe the world is inherently hierarchical. Conservatives, our work shows, tend to believe more strongly than liberals in a hierarchical world, which is essentially the view that the universe is a place where the lines between categories or concepts matter. A clearer understanding of that difference could help society better bridge political divides.

We discovered this by accident. My team was undertaking an ambitious effort to map all the most basic beliefs that people hold about the world we share. We call these tenets "primal world beliefs," or "primals" for short. Primals reflect what individuals think is typical about the world—for instance, that

Illustration by Chris Gash

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Jer Clifton directs the Primals Project at the University of Pennsylvania, where he teaches research methods in the Masters of Applied Positive Psychology program.



most things are beautiful or that life is usually full of pain and suffering. We suspect these beliefs hold important implications for people's mental health and well-being.

Our effort began with 10 projects to identify possible primals. As part of our work, we gathered data from more than 80,000 tweets and 385 influential written works, including the Bible and the Bhagavad Gita. From that information and several rounds of statistical analysis using data from more than 2,000 people, we identified 26 primals and found that most beliefs clustered into three categories of assumptions about the world: that it is generally dangerous or safe, dull or enticing, and alive or mechanistic. We have created a free, scientifically validated online survey if you wish to learn how your own primals compare with the average (search for "discover your primals").

In most of our studies, we also asked people to share their political party preference and to rate how liberal or conservative they consider themselves. In an early study focused on well-being, I noticed a surprising relation between people's beliefs and how they answered these two questions. Belief that the world was dangerous was not as linked to party or ideology as past research—including some of our own—said it should be.

We conducted nine more studies with nearly 5,000 participants, mostly Americans, to make sure we had it right. These studies pointed away from the "dangerous world" belief as the core difference between liberals and conservatives and toward a different primal called hierarchical world belief. That primal, we found, was 20 times more strongly related to political ideology than dangerous world belief.

People who score high in hierarchical world belief see the world as full of differences that matter because they usually reflect something real, inherent and significant. Such individuals often separate things of greater value from things of lesser value. You might imagine that to them the world looks full of big, bold black lines. In the opposite view—held by people with lower scores for this belief—differences tend to be seen as superficial and even silly. For those with this perspective, the world is mostly dotted lines or shades of gray. (To reiterate, primals concern *tendencies* only. Even people with a strong hierarchical world belief see some lines as arbitrary.) In our work, this primal was high in conservatives and low in liberals.

Most types of hierarchical thinking that have been studied, such as social dominance orientation, concern preferences about how humans should be organized. But hierarchical world belief relates to how people think the world actually is—regardless of what they'd like to see. In addition, this primal applies not only to human groups but to *everything,* including plants, other animals and inanimate objects. For people high in this belief, the universe is the kind of place where lines matter.

One reason our discovery is exciting is that it hints at ways to work through specific political deadlocks. For example, consider debates around LGBTQ+ topics. Conservatives may feel that the line separating men and women is natural and innate—a big, bold line—whereas liberals may see that distinction as more superficial and culturally based. Welfare payments and policies, too, might be seen through a hierarchical lens, with some assuming that lines between rich and poor often reflect meaningful differences in people's work ethic, talent, morality or value to society.

The line relevant to the abortion debate is perhaps conception. Conservatives believe this line marks the beginning of human life and thus matters a great deal. A nonhierarchical perspective would be that life emerges incrementally across many thresholds.

Immigration debates often involve literal lines, such as the border between the U.S. and Mexico. If nonhierarchical world belief shapes liberal thinking, then no one should be surprised that liberals deprioritize enforcing those boundaries.

Our discovery hints at ways to work through specific political deadlocks, such as debates around LGBTQ+ topics.

Knowing about the left-right split on hierarchical world belief could have practical value. In 1905 English author G. K. Chesterton wrote, "The most practical and important thing about a man is still his view of the universe." Although I might not go that far, Chesterton has a point. Whether you want to empathize with people on the other side, beat them in elections or convince them of a policy's merits, understanding others' primals can be useful. Again, primal world beliefs are about the world's tendencies—but people also expect some exceptions. That nuance creates an opening for productive debate.

For instance, imagine a liberal trying to convince a conservative to adopt a more inclusive policy on transgender issues. If they assume that conservative beliefs are informed by fear of danger, they might note that transgender people are much more likely to be assaulted than most other people are. But another tactic would be blurring lines—perhaps noting that a small but consistent number of babies are born with atypical genitalia and arbitrarily assigned a sex at birth, which suggests the line between male and female is not always perfectly clear. If hierarchical world belief is more at play than dangerous world belief, assuaging fears may be less effective than describing why a specific line is a bit arbitrary.

To reach a point of cooperation—even amid intense disagreement—people often need to grasp other perspectives. Our work shows that conservatives and liberals disagree more about the meaning of differences than about the prevalence of danger. That insight may seem modest, but it's a big step in the right direction. SA

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Worsening Light Pollution

We are losing our view of the sky at an astonishing rate of almost 10 percent a year

By Phil Plait

When I was a kid, my family lived in suburban Washington, D.C. This location made being a budding amateur astronomer tough; most stars were invisible against the overhead glare from city lights. At best there was only a hint of the diffuse Milky Way to see: the combined radiance of 100 billion stars was dimmed to near nothingness by bright streetlamps and storefronts.

This effect is light pollution—human-generated illumination cast up into the heavens—causing the sky itself to glow and washing out the stars. Astronomers have known for years that the situation is bad for stargazing, but it also has real and negative consequences for the well-being of many living things—plants, animals and even humans. More than 80 percent of humanity is affected by light pollution, our view of the skies being stolen away.

For most of us the stars are, in essence, going out.

And each year it gets worse. How much worse, exactly, has been hard to say. Light pollution has been measured from space, but orbiting satellites don't detect light the same way the human eye does, so they may not yield results that match what we see from the ground. When people look at the sky, what is the change in sky brightness they perceive over time?

To find out, a team of scientists led by light-pollution researcher Christopher Kyba of the GFZ German Research Center for Geosciences in Potsdam turned to what may seem like a weirdly obvious detection method: human beings.

They used data from Globe at Night, a project run by the U.S. National Science Foundation's National Optical-Infrared Astronomy Research Laboratory, which uses citizen science to measure light pollution. The process is brilliantly simple. Volunteer participants are given a set of star charts (created by Jan Hollan of the Global Change Research Institute of the Czech Academy of Sciences) that show the sky with a range of stars visible: one chart shows only the brightest stars, the next includes somewhat fainter stars, and so on down to the faintest stars visible to the naked eye under ideal conditions. Participants then look at the sky and compare the faintest stars they can see with the ones on the charts, choosing those that best match what they observe.

Kyba and his team examined an astonishing amount of data from more than 50,000 citizen scientists around the world who sampled their local sky brightness between 2011 and 2022. Although there was considerable place-to-place variability—for example, on average, Europe saw a 6.5 percent increase in light pollution annually, whereas North America saw a 10.4 percent increase—the researchers found that globally, light pollution increased by 9.6 percent a year over the study period.

This might not sound like much, but it reflects an exponential growth rate, similar to how compound interest accrues on a debt. A year-over-year growth of about 10 percent means sky brightness is doubling roughly every seven or eight years. A moment's thought should make clear why that is deeply troubling. As Kyba and his co-authors explain in their paper, published in January in the journal *Science,* if there are 250 visible stars in the sky when someone is born, by the time they're 18 they'll see only 100, and over that same period the sky will have increased in brightness by more than a factor of four.

This result is all the more alarming because of its potential implications for satellite-based measurements, which have recorded only an approximately 2 percent annual increase. Based on their work, Kyba and his team argue that the satellites are severely underestimating the effects, obscuring the possibility of a looming future in which almost everyone loses sight of the stars.

Technological changes can account for much of this discrepancy. For example, Kyba and his colleagues point out that over recent years many older outdoor lightbulbs that emitted redder light have been replaced by LEDs that shine more brightly in blue—a color that scatters more easily in the atmosphere and to which many Earth-observing satellites' detectors are less sensitive. Moreover, satellites mostly see light that shines straight upward, such as from cities and poorly constructed streetlights, rather than horizontally cast rays from windows or billboards, which can greatly affect observers on the ground.

All this extra light at night has a large effect on the life under it. Researchers have shown that it negatively impacts many animals and plants: light pollution disrupts the migrations of birds, the delicate blossoming of flowers and even the luminous courtship of fireflies, to name just a few examples. It affects humans as well, possibly triggering insomnia, among many other health problems.

In some ways, this is reminiscent of the climate crisis: global in nature, difficult to notice day by day, and hard for individuals to grasp and mitigate on their own. I suspect, however, that if global warming increased by some 10 percent a year, we would have long ago tackled the issue head-on.

Worse, light pollution puts on a friendly face for many people who think increased light at night automatically means increased safety. Although more light does help in some cases—for example, illuminated roads make it easier for drivers to see at night—it isn't guaranteed to protect us as much as people might think. And on average, this increased illumination just throws even more unwanted light upward.

So what can we do about our brightening skies?

There is a lot already happening. Groups such as the International Dark-Sky Association, or IDA, advocate not for more lighting but for more intelligent lighting—smarter streetlights that concentrate their light downward are one example. Because these lights offer more efficient illumination, they save energy, too, eventually paying for themselves. IDA offers advice on how to contact local authorities about installing better fixtures and creating ordi-

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Stars shine over a nature reserve in Andalucia, Spain, with city lights in the distance.

Estellez/Getty Images

nances to reduce pollution. A number of cities in the U.S. and other countries are designated Dark Sky Communities, meaning they have shown "exceptional dedication to the preservation of the night sky" by discouraging wasteful lighting practices.

At the moment, simple awareness is one of our greatest benefits. Turning off your own outdoor lighting at night might not seem like a big deal, but if you tell others, that helps. Awareness grows. Any cause like this one needs a critical mass to get widespread notice, so everyone who participates can add to the solution.

Still, local solutions, such as the recent successes in Pittsburgh and Fort Collins, Colo., don't readily translate to global progress. This kind of change isn't easy for everyone; many areas in developing nations have dangerously insufficient lighting at night and use wasteful greenhouse gas–emitting fuels to power the meager light sources they have. More lighting could help people living there out of poverty but at the cost of a larger increase in sky glow. The research by Kyba and his team didn't cover developing nations well, so it's not clear at what rate their light pollution is increasing. But it's obvious enough that more efficient lighting would benefit these regions, too, if for no other reason than it would keep their costs down in the medium to long run.

In an epic thread on Twitter, Kyba goes over the methodology and results of his group's work and includes some advice on what individuals can do. He suggests using targeted illumination rather than flood lighting, deploying outdoor lighting only when needed, and opting for lightbulbs and LEDs that shine more red than blue to reduce how much light scatters across the sky.

We do need bigger and smarter solutions. Certainly the physical and biological effects of light pollution are a big concern, but more is at stake here: the loss of beauty and our connection to nature. The night sky is, quite simply, gorgeous, with treasures scattered among the stars. Going out under that velvet vault and watching a meteor shower or a lunar eclipse is a wonderful way to spend time with family and friends or to simply decompress. To see the stars is to nourish the soul. I've seen (and heard) countless owls and coyotes and other wildlife while outside at night, and observing the heavens gives me a profound appreciation of the natural world around me. The awe of the night sky is very real.

This isn't just a matter of a few inconvenienced astronomers. It's the equivalent of shuttering the Louvre, of closing concert halls, of mowing down vast fields of wildflowers. I wonder how deep my own love of astronomy would have become had I stayed in the suburbs of D.C., where the starlight would have diminished, not so gradually, as I grew up. I struggled to see the skies through that miasma as it was; only a profound love of astronomy kept me going. Many people don't even know that they—and their descendants—are losing this cosmic experience just over their heads.

We need the dark night sky, and it's up to all of us to make sure it's still there every time the sun goes down. SA

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NONFICTION

Uncontrolled Burn

Absurdity reigns when a wildfire threatens a town purpose-built for oil extraction

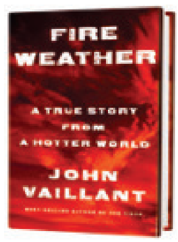
Review by Abe Streep

In May 2016 a wildfire started near Fort McMurray, the boomtown built around the oil sands in Alberta, Canada. The fire grew to almost 1.5 million acres and became its own kind of weather system, creating fearsome pyrocumulonimbus clouds that made their own lightning. It was a vivid modern allegory: a blaze of biblical proportions threatening one of humanity's greatest acts of hubris.

Few writers were better positioned to tell the story than John Vaillant, a Vancouver-based journalist and novelist who is at his best in the fraught places where desperate humans clash with their habitats. Vaillant's gorgeous first book, *The Golden Spruce,* centers on an act of eco-sabotage in the Haida Gwaii archipelago in Canada, and he rose to wider prominence with *The Tiger,* a bestselling account of a predator that seemed to take vengeance on hunters in eastern Russia. In *Fire Weather,* Vaillant travels to a city where money rules, nature is an object of conquest, and a ridge on the land has been "weeping raw bitumen that glistened like liquid obsidian."

Meanwhile North America is caught in a human-made wildfire deficit because a century of suppression has created dense layers of timber primed to burn. In Alberta's subarctic boreal forests, thick with spruce and aspen, those fires are often massive. "When it burns, it goes off like a carbon bomb," Vaillant writes.

To narrate the events of the summer of 2016, Vaillant reconstructs the actions of an oil-sands employee, multiple firefighters and the much maligned emergency-response leadership, among others. Their experiences contain ample drama, but their lives rarely connect. Fort McMurray, like many boomtowns, is a transient place. "Nobody retires here, nobody dies here," a pastor named Lucas Welsh tells Vaillant. They also don't seem to interact that much. In this relational void, where the story often feels fractionated rather than woven, the wildfire itself emerges as the book's main character. The choice feels intentional—the blaze's fury has a thematic resonance with the tiger's—and Vaillant goes to great lengths to demonstrate that humans have invited a comeuppance. "Miles above the city, hurricane-force downdrafts hurled fusillades of black hail back to earth," Vaillant writes, "just as they had done in ancient Egypt."



Fire Weather: A True Story from a Hotter World
by John Vaillant.
Knopf, 2023 ($32.50)

In recent years some journalists who write about wildfires have begun avoiding this supercharged language of aggression. The ingrained Western tendency to characterize wildfire as invading and monstrous reinforces a colonial assumption that we can live apart from what is a natural and regenerative force. Vaillant repeatedly frames the fire in explosive or biblical terms and the subsequent effort to save Fort McMurray as a war, with firefighters pitted against the flames. The effect is certainly dramatic, and it underscores his central point that megafires such as this one are not entirely natural and are exacerbated by oil-driven greed. "If unregulated free market capitalism were a chemical reaction," he writes, "it would be a wildfire in crossover conditions."

His reporting on the phenomenon of "crossover"—described here as the moment when temperature surpasses relative humidity and a blaze is unleashed—is captivating, as is the insight that the combustive energy released in Fort McMurray was comparable to a nuclear bomb's. But Vaillant also characterizes the wildfire as a "regional apocalypse" and imminent flashover—the point of spontaneous combustion in an enclosed space—as "a malevolent entity from another dimension breaking through to this one."

In *The Tiger,* Vaillant toed an awfully fine line to take the reader inside the cat's mind, using science reporting and a rigorous story structure to propel a thriller of natural history. In *Fire Weather,* there are



Illustration by London Ladd

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fewer narrative guardrails, and as a result the book can feel meandering, with digressions that seem indulgent. One chapter is dedicated to the idea, proposed by Vaillant, that the human species should be renamed *Homo fraglans,* liberally translated as "burning man." There are epigraphs from Ovid, Herman Melville and Shakespeare; when one from Cormac McCarthy's *The Road* appears at the top of another chapter, it feels almost inevitable.

In moments of focus, *Fire Weather* is animated by a fascinating history of regional exploitation and illustrative absurdities from a get-rich-quick city burning down. A fleeing resident insists on locking his door as flames engulf his street; a golfer, freshly evacuated from the course, stops to pick up his dry cleaning; a student actually tells her brother, "Don't look up!"

There's a memorable character named Wayne McGrath, one of many Newfoundlanders who came to Fort McMurray after the collapse of the cod industry—an earlier environmental fiasco created by capitalistic appetites. McGrath goes to astonishing efforts to save a beloved Harley-Davidson before riding into the sunset.

McGrath's troubling story doesn't end there, and it alone might have been enough to anchor the narrative—as might the experiences of the firefighters who courageously fought the blaze when, as Vaillant beautifully writes, "even the ravens had fled."

But Vaillant seeks to wrangle something still more grandiose from the material, and in his frustration with our collective failures, he leaves behind many of his characters. He is not the first great writer to point out that, in an age of greed, we could all do with more restraint. He's also not the first to veer into unrestrained activism at the expense of a story—one that, in this case, was powerful enough on its own merits.

Abe Streep is a journalist based in Santa Fe, N.M., and author of *Brothers on Three: A True Story of Family, Resistance, and Hope on a Reservation in Montana* (Celadon, 2021).

FICTION

Invasion Meme

An alien-induced existential crisis in the online age

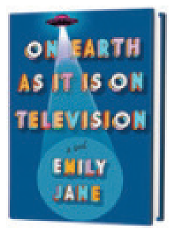


Glittering, strange spaceships appear and hover over every major city on Earth; yes, that's familiar. What is unfamiliar about this debut from Emily Jane is the way first contact with an alien species brings people together and how it tears them apart—as well as the major role of cats.

Written for an extremely online age, *On Earth as It Is on Television* follows a handful of characters, each of whom must decide who they will be in a world fundamentally changed by the knowledge that we are not alone and are never unwatched. It brings readers into the mind of a long-comatose man named Oliver, whose first hint of consciousness in 20 years coincides with the invasion. It grants a beguiling window into the marriage of Blaine and his wife, who look perfect from the outside but start to disintegrate the minute the world changes. It asks deep questions about what constitutes a meaningful life through Heather, a woman who realizes she mostly has not lived one, so far.

The novel also follows the epic adventure of a "chonky boi" cat named Mr. Meow-Mitts, who receives a mysterious message to "run run run" toward a gathering of cats when the aliens land. The language of cat adoration is spread thick, as charming as buttercream and equally sweet.

If you enjoyed Lindsay Ellis's *Axiom's End* but prefer lighter fare, you'll find deep comfort and joy in Jane's exploration of what it means to be alien and how we all take turns being on the outside. Like a science-fiction novel that runs in the margins of I Can Has Cheezburger? memes, *On Earth as It Is on Television* is an unusually fun and absurd take on what might otherwise be just another imitation of *Independence Day* or *The Day the Earth Stood Still.* It is smart about consumer culture and the American yearning to turn everything into reality TV without using those smarts to bite. In this way, Jane's work is a fine example of what is often called noblebright fiction (as an alternative to the subgenre of grimdark): it serves up heart, but nobody had to be cut open to obtain it. *—Meg Elison*



On Earth as It Is on Television
by Emily Jane. Hyperion Avenue, 2023 ($27.99)

IN BRIEF

I Feel Love: MDMA and the Quest for Connection in a Fractured World
by Rachel Nuwer. Bloomsbury, 2023 ($28.99)



If you're looking to parse the hype about MDMA, this excellently researched book by *Scientific American* contributor Rachel Nuwer gathers perspectives from skeptics and supporters alike: law enforcement, psychiatrists, and people with past and present experience taking the drug. Nuwer's journalistic instinct to cover warnings of its possible physiological effects and to advocate for law-abiding behavior cleverly plays off her analysis of the political broadsides that have long maligned the drug's reputation. The compelling narrative, woven from emotional testimonials and clinical studies, makes a convincing argument for MDMA's potential as a therapeutic supplement, especially for those working through trauma. *—Sam Miller*

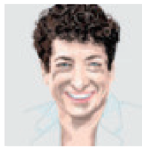
Tiger Work: Poems, Stories and Essays about Climate Change
by Ben Okri. Other Press, 2023 ($24.99)



Rejecting the term "climate emergency" in favor of "humanity emergency," Ben Okri puts forth an indictment of humanity that is counterbalanced only by his belief in its capacity for evolution. Although his collection is diverse—it includes poems about plastic, parables about water, a letter to Earth and vignettes describing our civilization in its waning days—Okri's simple, stirring language runs through it like a current, delivering unexpected shocks of both pain and inspiration. Imbued with an "existential creativity to serve the unavoidable truth of our times," this volume offers an unflinching vision of who we are and who we must become to survive. *—Dana Dunham*

Javier Zayas Photography/Getty Images; 4khz/Getty Images (*backgrounds*); KTSDESIGN/Science Photo Library/Getty Images (*flying saucer*); SensorSpot/Getty Images (*cat*); Scientific American (*composite*)

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Naomi Oreskes is a professor of the history of science at Harvard University. She is author of *Why Trust Science?* (Princeton University Press, 2019) and co-author of *The Big Myth* (Bloomsbury, 2023).



Fusion's False Promise

Despite a recent advance, nuclear fusion is not the solution to the climate crisis

By Naomi Oreskes

In December 2022 scientists at the U.S. National Ignition Facility (NIF) announced a breakthrough in the decades-long effort to create an energy source based on the same nuclear fusion reactions that power the sun. An "engineering marvel beyond belief," they proclaimed, as major newspapers quickly followed with breathless coverage. The *Washington Post* called it "truly something to celebrate." Other commentators gushed about the fusion future as a solution to clean energy, global poverty, perhaps even world peace.

On inspection, the advance was rather less sensational than these reports suggested. The researchers had achieved what is known as ignition, the condition where a fusion reaction produces more energy than it took to start it. But the scale of the accomplishment is not remotely close to what would be required to generate electricity for practical use, much less herald a new era of clean energy [see "Star Power," on page 28]. The power demands as reported didn't include the power needed to build the equipment and gear it up; the entire event lasted just a few seconds. And, ironically, the higher-than-expected energy yield damaged some of the diagnostic equipment in the experimental setup, casting doubt on whether ignition had even been achieved.

Calling this development a breakthrough in achieving "limitless zero-carbon power," as the *Financial Times* put it, is like claiming that the discovery of fire was a milestone on the path to electricity. Hype like this doesn't help the scientific community to build and maintain public trust; it risks diverting resources away from actual solutions to the climate crisis.

Scientists started working on creating fusion reactions in 1942 as part of the Manhattan Project. Physicist Edward Teller wanted to focus their attention on building a fusion bomb. That proved unrealistic, and just as a fusion bomb took a back burner to a fission weapon during the war, civilian fusion power took a back burner to fission after the war. On the sun, fusion takes place at millions of degrees. The scientific and technical challenges of harnessing fusion on Earth were simply overwhelming.

In the 1960s and 1970s physicists realized they could use lasers to heat hydrogen to a sufficiently high temperature before the gas could escape. After decades of limited progress on controlled fusion reactions, Congress allocated funds for the NIF. Construction began in 1997; the first experiments began in 2009. At the time, NIF physicist Siegfried Glenzer predicted ignition within the year.

Given the short time frame we have to face the climate crisis—achieving "deep, rapid and sustained global greenhouse gas emissions reduction" as soon as possible, in the words of the Intergovernmental Panel on Climate Change—how do we decide whether the cost of fusion research is worth the potential benefit or whether the money would be better spent elsewhere? How do we differentiate between staying the course and throwing good money after bad?

The NIF cost $3.5 billion to build, and its current annual budget is $380 million. The Fusion Energy Sciences program at the U.S. Department of Energy is slated to receive an additional $763 million, for a total of about $1.1 billion (an amount that the fusion industry says is far too low). By comparison, the 2022 budget of the National Renewable Energy Laboratory was $671 million.

Federal funding for nuclear power has long dwarfed funding for renewable energy and efficiency. According to the Congressional Research Service, from 1948 through 2018, 48 percent of federal energy R&D went to nuclear (both fission and fusion), whereas less than 13 percent went to renewables and 11 percent to energy efficiency. In 1948 that apportioning made sense because fission and fusion seemed promising, and no one much saw the need for efficiency. But the pattern has persisted: between 1978 and 2018 the share of renewables was 18 percent.

For 75 years the U.S. federal government has invested heavily in fission and fusion nuclear power with only modest gains to show. So why are we focusing on a speculative technology that will almost certainly come too late to make a meaningful contribution to avoiding climatic catastrophe?

Don't get me wrong. We *should* fund fusion research because even $1.1 billion is no more than it costs per year to maintain a single aircraft carrier. But fusion is a long game that may or may not pay off. It's not an answer to the climate crisis. SA

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Illustration by Izhar Cohen

50, 100 & 150 YEARS AGO

INNOVATION AND DISCOVERY AS CHRONICLED IN *SCIENTIFIC AMERICAN*

Compiled by Mark Fischetti

JUNE

1973 John Keats, Poet and Surgeon

"Poet John Keats died tragically early, in 1821, at the age of 25, of tuberculosis. But few people are aware that he crowded two careers into his brief life: he studied medicine and was trained in surgery for as many years as he wrote poetry. Even people who know of Keats's early training have assumed that he was pushed into medicine against his will, resented it and left it as soon as possible. Not so, according to Robert Gittings, an English biographer of Keats. The poet picked a medical career on his own, worked hard at a sound training program and did well, and had actually qualified as a general practitioner when he gave up medicine to devote the rest of his life (four years, as it turned out) to the joys and pain of writing."

Computer Chess Champ

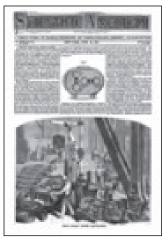
"It has now been 24 years since Claude Shannon outlined how a computer could play chess. Last August, while Bobby Fischer was winning the world chess title from Boris Spassky in Iceland, several computers were quietly contending in Boston for the U.S. computer chess championship. The winning machine, a Control Data Corporation 6400, was not actually present; its moves were relayed from Northwestern University in Evanston, Ill., where its program, known as Chess 3.5, had been written. The program is fundamentally different from all previous programs in that it can take advice from a master. Writing in *Scientific American* in February, 1950, Shannon explained why he thought the chess-playing problem merited attention: 'The problem is sharply defined, both in the allowed operations (the moves of chess) and in the ultimate goal (checkmate). It is neither so simple as to be trivial nor too difficult for satisfactory solution.'"



1973



1923



1873



1973, Digital Displays: Electr onic nu er s are eco ing a a iliar sight on consu er ite s such as oc et calculators digital cloc s and electronic atches Three t es o arra s ha e een de elo ed The si lest is the se en-stro e arra *top* asicall a rectangle ith a hori ontal ar The our- -se en dot arra *middle*) also is a rectangle with a horizontal bar. The five-by-seven array (*bottom* has dots it can also generate all the letters o the al ha et

1923 Alcohol as Fuel, Not Drink

"Before prohibition the per capita consumption of gasoline and alcoholic beverages was about the same, 20 gallons a year. Now consumption of alcohol is theoretically zero, while gasoline has risen to 77 gallons. However, we may live to see these ratios reversed, as people get accustomed to regard alcohol as fuel instead of as food, and the vexatious restrictions that have been imposed upon it for the last 500 years may be removed. When that day comes the Government will be urging people to set up home stills instead of confiscating them, and this will enable spoiled grain, unsalable fruit, sawdust and all sorts of wasted stuff to be distilled into fuel on the spot."

H. G. Wells on *Scientific American*

"H. G. Wells, in an article entitled 'What Everyone Should Read' appearing in the *American Magazine*, has a kind word for us. The great British historian and novelist says, in part: 'Everyone, I think, should read such a weekly newspaper as *Nature*, of London, within its range the most honest and wonderful newspaper in the world, or the *Scientific American*, to keep in touch with the ever-advancing boundaries of human knowledge and achievement. If there are people who cannot read such periodicals, then it is high time the schools that produce such people were looked into and shaken up to a higher level.'"

1873 Private Bathing for Birds

"The shyness of birds in performing their ablutions is well known, but no inventor has applied their powers on behalf of the feathered tribe, and they have been obliged to wash themselves in public. Cage birds have especially suffered. But G. T. Peters of Jersey City, N.J., has lately patented a bath tub for birds, in which a hood covers the water dish. The entrance is on one end only, and birdy creeps therein, as into a diminutive bathroom, to enjoy a swim without spattering the cage, in water not soiled by matter falling from the perches."

Scientific American, Vol. 228, No. 6; June 1973

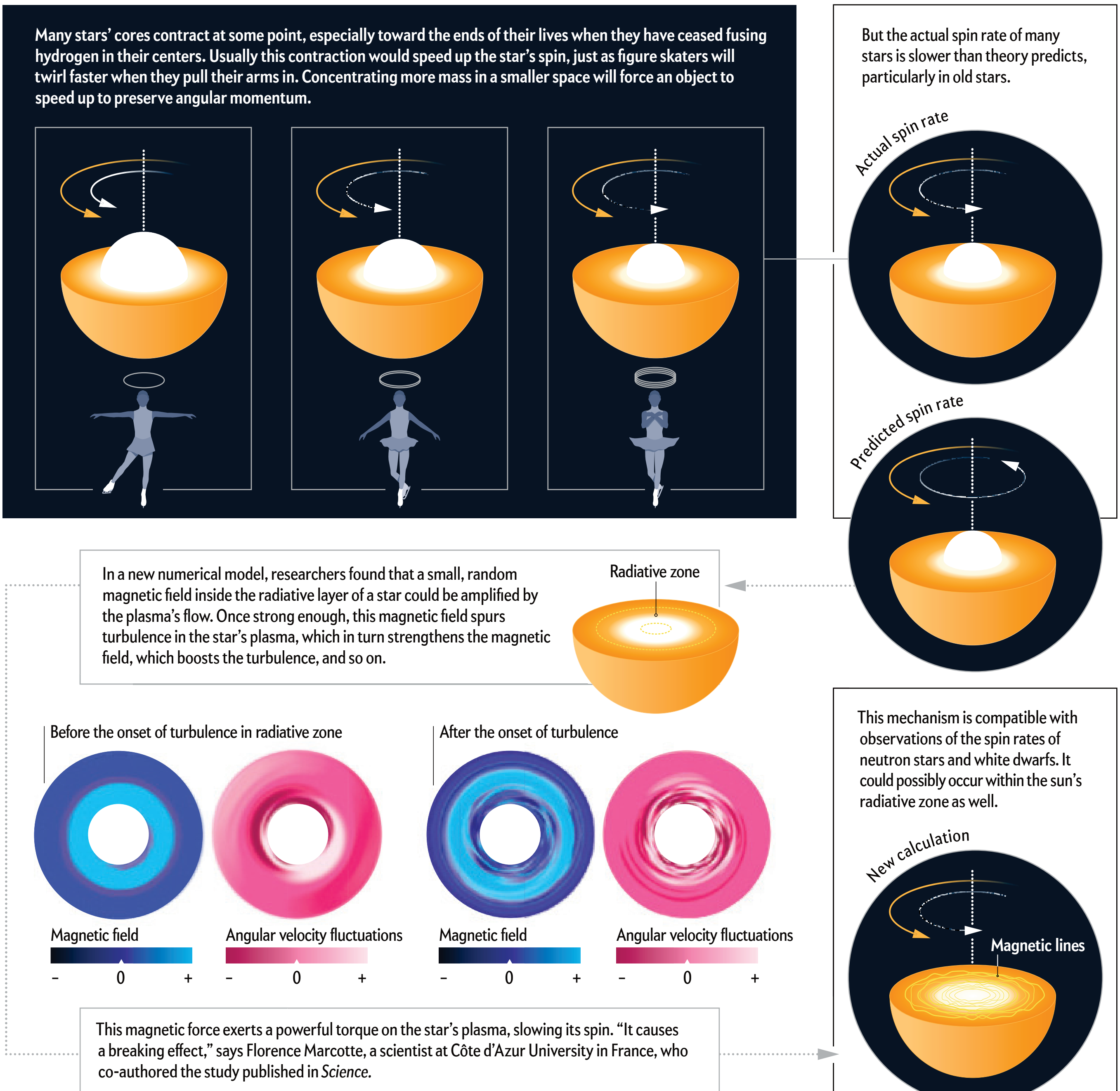
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Text by Clara Moskowitz | Graphic by Lucy Reading-Ikkanda

Star Spin Mystery

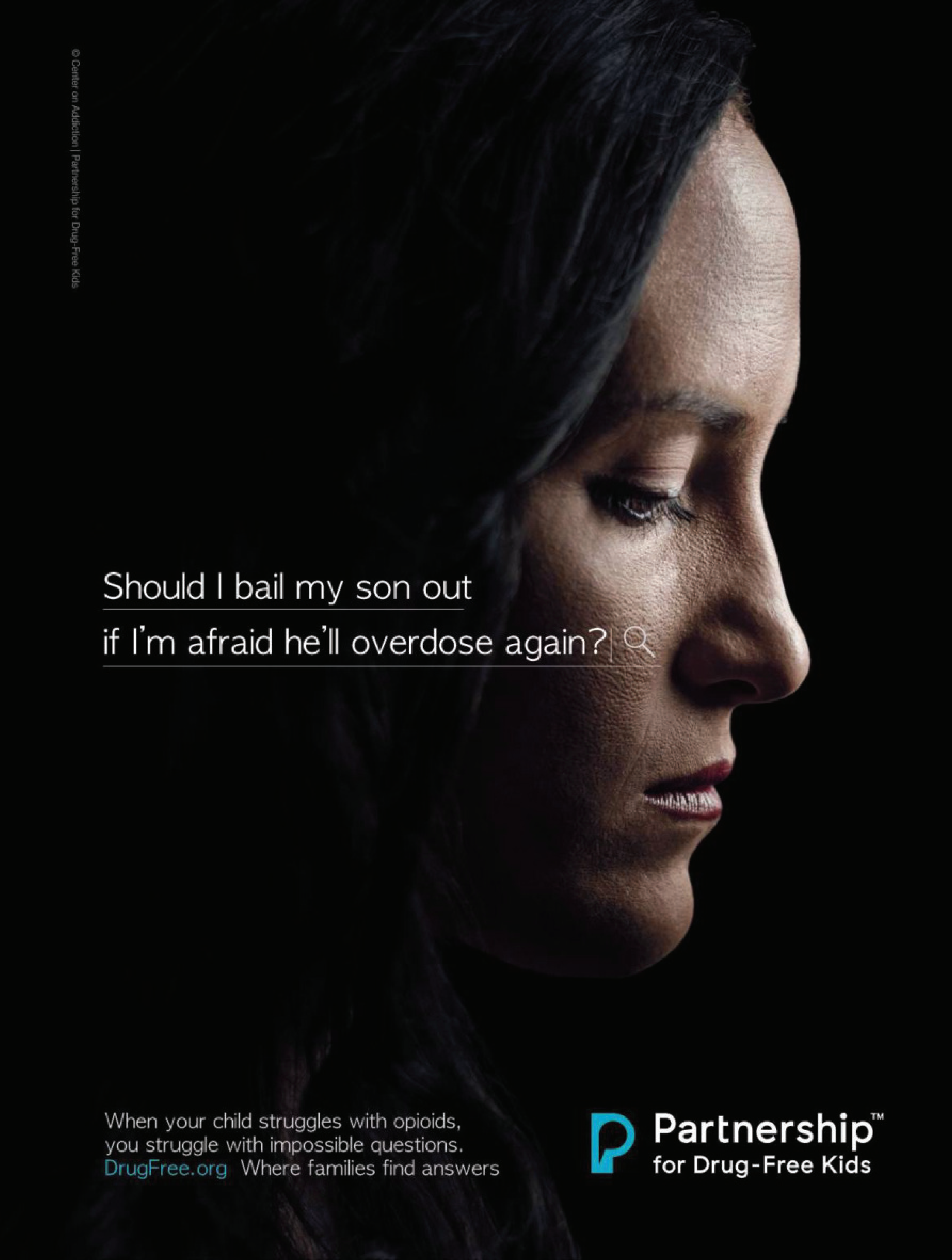
Scientists wondered why the insides of stars are spinning so slowly

Astronomers can measure how fast stars spin by observing "starquakes"—seismic tremors that are the equivalent of earthquakes on our planet. Yet these observations have posed a puzzle because many stars seem to be spinning slower than they should be. In a new study, researchers modeled how a magnetic field could grow in the internal layers of a star, dragging its rotation down.



Source: "Spin-Down by Dynamo Action in Simulated Radiative Stellar Layers," by Ludovic Petitdemange, Florence Marcotte and Christophe Gissinger, in *Science*, Vol. 379; January 20, 2023 (*reference*)

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